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# FRAMEWORK GUIDANCE MANUAL FOR IN SITU WETLAND RESTORATION DEMONSTRATION


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This Framework Guidance Manual (FGM) provides guidance to Department of Defense (DoD) end-users and to the broader environmental site remediation community on the use of reactive amendment in situ technologies for the remediation of contaminated wetland hydric soils. It serves as a scientific and engineering reference document for the evaluation of in situ remedies that involve addition of reactive amendments or sequestration agents to address persistent contaminants in hydric soils. The methods described provide the user with a toolbox of methods with which to approach site characterization/ monitoring, treatability testing and demonstration, and remedy implementation.
This FGM: (1) provides a repository of literature sources for active in situ remedial projects, (2) outlines conceptual approach to managing the remediation of wetlands hydric soils, (3) includes suggestions for project objectives, metrics, and evaluation criteria, (4) provides discussion of implementation means and methods, and (5) supports an assessment of the technology cost. Although developed for the Department of Defense project manager, this FGM may be useful for other agencies evaluating potential remedies for contaminated wetlands or professional practitioners seeking solutions for public and private sector clients.

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# Framework Guidance Manual for
# In Situ Wetland Restoration Demonstration

## ESTCP Project ER-200825

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# List of Acronyms

| | |
|---|---|
| AAP | Agglomerated Amendment Pellets |
| AASHTO | American Association of State Highway and Transportation Officials |
| AC | Activated Carbon |
| AFCEE | Air Force Center for Environmental Excellence |
| APG | Aberdeen Proving Grounds |
| ARARs | Applicable or Relevant and Appropriate Requirements |
| ARCS | Assessment and Remediation of Contaminated Sediments |
| ASTM | American Society for Testing and Materials |
| AVS | Acid Volatile Sulfide |
| BAZ | Biologically Active Zone |
| CERCLA | Comprehensive Environmental Response, Compensation, and Liability Act |
| COC | Contaminant of Concern |
| CSM | Conceptual Site Model |
| CPS | Composite Particle Systems |
| CU | Consolidated, Undrained |
| CWA | Clean Water Act |
| CWMDP | Chemical Warfare Material Degradation Product |
| DDD | Dichloro-Diphenyl-Dichloroethane |
| DDE | Dichloro-Diphenyl-Dichloroethylene |
| DDT | Dichloro-Diphenyl-Trichloroethane |
| DDx | Total DDT, i.e. the sum of DDT, DDE, and DDD |
| DET | Diffusive Equilibrium in Thin Films |
| DGT | Diffusive Gradients in Thin Films |
| DOC | Dissolved Organic Carbon |
| DoD | Department of Defense |
| DON | Department of Navy |
| DQO | Data Quality Objectives |
| EMNR | Enhanced Monitored Natural Recovery |
| ENR | Enhanced Natural Recovery |
| EPA | (United States) Environmental Protection Agency |
| ERDC | Engineer Research and Development Center |
| ERDC WES | Engineer Research and Development Center Waterways Experiment Station |
| ESTCP | Environmental Security Technology Certification Program |
| FAA | Federal Aviation Administration |
| FGM | Framework Guidance Manual |

| | |
|---|---|
| FRTR | Federal Remediation Technologies Roundtable |
| FS | Feasibility Study |
| HASP | Health and Safety Plan |
| HOCs | Hydrophobic Organic Contaminants |
| ITRC | Interstate Technology and Regulatory Council |
| LFT | Linear Feet |
| MNR | Monitored Natural Recovery |
| MRP | Munitions Response Program |
| NAPL | Non-aqueous Phase Liquid |
| NAS | National Academy of Sciences |
| NAVFAC | Naval Facilities Engineering Command |
| NAVFAC EXWC | Naval Facilities Engineering and Expeditionary Warfare Center |
| NAVFAC LANT | Naval Facilities Engineering Command, Atlantic Division |
| NRC | National Research Council |
| NRCS | National Resource Conservation Service |
| NOAA | National Oceanographic and Atmospheric Administration |
| NWCA | National Water Condition Assessment |
| OC | Organoclays |
| O&M | Operations and Maintenance |
| ORP | Oxidation-Reduction Potential |
| OSWER | Office of Solid Waste and Emergency Response |
| PAC | Powdered Activated Carbon |
| PAH | Polycyclic Aromatic Hydrocarbon |
| PBT | Persistent, Bioaccumulative, and Toxic |
| PCB | Polychlorinated Biphenyl |
| PEDs | Polyethylene Devices |
| PMO | Project Management Office |
| POM | Polyoxymethylene |
| ROD | Record of Decision |
| RCMs | Reactive Core Mats |
| RPM | Remedial Project Manager |
| SEM | Simultaneously Extracted Metals |
| SERDP | Strategic Environmental Research & Development Program |
| SPMD | Semipermeable Membrane Devices |
| SPME | Solid Phase Microextraction |
| TBC | To Be Considered |

| | |
|---|---|
| TIE | Toxicity Identification Evaluation |
| TLC | Thin Layer Cap |
| TOC | Total Organic Carbon |
| UNH | University of New Hampshire |
| USACE | U.S. Army Corps of Engineers |
| USAF | U.S. Air Force |
| USC | United States Code |
| USEPA | United States Environmental Protection Agency |
| USFWS | United States Fish and Wildlife Service |
| USGS | United States Geological Survey |
| UU | Unconsolidated, Undrained |
| VOCs | Volatile Organic Compounds |
| ZVI | Zero-valent Iron |

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# Executive Summary

Wetland systems provide valuable habitat that is ecologically vulnerable when aggressive remedial technologies are applied to address anthropogenic contamination in hydric soils, yet wetland soils commonly serve as contaminant sinks because of their high organic matter content, proximity to developed industrial sites, and co-occurrence with waterways. Hydric soils potentially trap and serve as reservoirs for persistent organic and inorganic contaminants that may pose a potential risk to human health and the environment. Therefore, a need for the development of remedial technologies that can effectively and efficiently address risks and preserve beneficial habitat was identified.

This Framework Guidance Manual (FGM) provides guidance to Department of Defense (DoD) end-users and to the broader environmental site remediation community about the use of reactive amendment *in situ* technologies for the remediation of contaminated wetland hydric soils. This manual was prepared to serve as a scientific and engineering reference document for the evaluation of *in situ* remedies that involve addition of reactive amendments or sequestration agents to address persistent contaminants in hydric soils. This FGM was not designed to be a comprehensive *in situ* wetland remediation handbook, but rather presents a generalized framework to assist end-users with evaluation of the applicability and efficacy of these technologies given site-specific considerations. The methods described in this FGM are intended to provide the user with a toolbox of methods with which to approach site characterization/monitoring, treatability testing and demonstration, and remedy implementation.

This FGM is intended to help support the following needs: (1) provides a repository of literature sources for active *in situ* remedial projects, (2) outlines conceptual approach to managing the remediation of wetlands hydric soils, (3) includes suggestions for project objectives, metrics, and evaluation criteria, (4) provides discussion of implementation means and methods, and (5) supports an assessment of the technology cost. Although developed for the Department of Defense project manager, this FGM may be useful for other agencies evaluating potential remedies for contaminated wetlands (e.g., United States Environmental Protection Agency, Federal Aviation Administration) or professional practitioners seeking solutions for public and private sector clients.

An attempt to reflect the current state of the technology is made with a literature review of laboratory and field demonstration projects. The summaries of results presented herein should be consulted for general preliminary guidance, but the end user of this FGM is encouraged to conduct a comprehensive literature search as the transfer of technology innovations is rapidly advancing. The amendments reviewed in this FGM include activated carbon (AC), organoclay, and apatite. Of these amendments, AC has been the most researched in wetland hydric soils and as such is included in discussions throughout. In a similar vein, the application of AC to treat hydrophobic organic contaminants (HOCs) and, to lesser extent inorganic constituents, is included in discussions in the FGM. Other contaminants not directly discussed (e.g. unexploded ordinances) may similarly be good candidates for the application of active *in situ* remediation in wetlands. Because the technology is developing, its application to a broader suite of contaminants and new amendment products may begin to emerge as the technology matures. For this reason, the end-user is encouraged to disseminate lessons learned to other practitioners to advance the acceptance and further refinement of this technology.

# 1.0 Introduction

This Framework Guidance Manual (FGM) provides guidance to Department of Defense (DoD) end-users and to the broader environmental site remediation community about the use of reactive amendment *in situ* technologies for the remediation of contaminated wetland hydric soils. This manual was prepared to serve as a scientific and engineering reference document for the evaluation of *in situ* remedies that involve addition of high value reactive amendments or sequestration agents to address persistent contaminants in hydric soils. This FGM was not designed to be a comprehensive *in situ* wetland remediation handbook, but rather presents a generalized framework to assist end-users with evaluation of the applicability and efficacy of these technologies given site-specific considerations.

This framework offers guidance relative to the following key *in situ* wetland remediation topics:

1. Evaluation of site conditions to determine whether addition of *in situ* amendments represents a viable remedial technology and to facilitate selection of appropriate treatment method(s) for impacted wetland hydric soils;
2. Determining critical design parameters;
3. Evaluating treatment performance at bench and pilot scale levels;
4. Considerations for full scale implementation of the technology, include cost analysis, and
5. Post-treatment performance monitoring and maintenance.

This FGM was informed in part based on the outcomes of a recently completed pilot scale technology demonstration project that targeted the treatment of polychlorinated biphenyls (PCBs) in a tidally influenced estuarine wetland system (In Situ Wetland Remediation, Environmental Security Technology Certification Program [ESTCP] Project No. ER-200825). Thus, it is informed by the conditions encountered and outcomes from that study. In addition, an effort has been made to include related recently completed and ongoing case studies to provide a broader perspective of the state of this technology. Information about the ESTCP Program and related projects can be accessed at http://www.serdp-estcp.org/Program-Areas/environmental-Restoration.

This manual is applicable to hydrophobic organic contaminants (HOCs) and metals in wetlands of all classifications where hydric soils are contaminated and remedial action is required. However, it is recognized that concepts and practices for design and construction considerations or for full scale remedy implementation discussed in this manual may be applicable to a broader suite of sites and compounds than discussed.

In addition to serving DoD end-users, this FGM is also intended to facilitate technology transfer to other scientific and engineering end-users. Critical concepts, applicable regulations, laws, and relevant guidelines are discussed. Potential treatment amendments and delivery methods are described, and the appropriate application of *in situ* technologies is assessed.

This manual has been written specifically to address wetland contamination concerns, but elements may also be applicable to sediment in sub-aqueous aquatic environments. For the purposes of this FGM, wetlands are defined per the U.S. Army Corps of Engineers (USACE) Wetland Delineation Manual guidelines as “those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas.” (USACE, 1987). According to the USACE Manual, hydric soils are a diagnostic environmental characteristic of wetlands. In this FGM, the term “hydric soil” refers to a soil that formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part (National Resource Conservation Service [NRCS], 2010; Federal Register July 13, 1994). Therefore, the term hydric soil in this FGM refers to all soils present within a wetland (including subaqueous sediment and soil).

## 1.1 Problem Statement

Wetlands provide critical ecosystem functions and are often sensitive to disturbances related to environmental contamination (Lewis et al., 1999). This sensitivity is due to their geographic proximity to industrial manufacturing and storage locations; hydrological locations at the interface of terrestrial runoff, groundwater and surface water bodies; natural adsorptive properties and the diverse biological communities inhabiting them. As a result, wetlands have historically been the receptors of industrial outflows and spills and they often act as sinks for both organic and inorganic compounds that can accumulate in high concentrations over time. Common contaminants of concern (COCs) in wetlands at DoD installations include persistent, bioaccumulative, and toxic (PBT) compounds [e.g., PCBs, Dichloro-Diphenyl-Trichloroethane (DDT) and its breakdown products, Dichloro-Diphenyl-Dichloroethane (DDD) and Dichloro-Diphenyl-Dichloroethylene (DDE) (termed DDx for all three compounds combined)], as well as inorganic constituents (e.g., copper, lead, and other metals) and potentially energetics from firing range operations.

The Army, Navy, and Air Force have millions of dollars of potential cleanup liabilities associated with contaminated wetlands (Figure 1-1). A limited informal survey of Navy project managers identified approximately 7,000 acres of contaminated wetlands and a number of sites where substantial and costly wetland remediation plans are currently in place (Amy Hawkins, personal communication). These wetland sites fall within broader DoD sediment liabilities, which are not insignificant. For instance, the Navy has more than 200 contaminated sediment sites (as of Fall 2010) with projected remediation cost of $1.3 billion; munitions Response Program (MRP) sites add another $1 billion of potential liability. The United States Environmental Protection Agency (USEPA) is currently conducting a National Wetland Condition Assessment (NWCA), which will provide the first-ever regional and national estimates of wetland ecological integrity and rank the stressors most commonly associated with impaired conditions. The final report is anticipated for release at the end of 2013. In addition to efforts by DoD and USEPA to catalog and understand the impacts of contamination on wetlands quality, the Federal Aviation Administration (FAA) is interested because airports are also recognized as having significant contaminated wetlands liabilities (National Academy of Sciences [NAS], 2011). The liabilities faced by the FAA result from the development of wetland habitats in stormwater ponds and ditches on airport properties that receive fuel-impacted runoff. These wetlands are sometimes home to threatened and endangered species. Thus, a concerted effort by multiple agencies is currently underway to estimate the liabilities associated with the degradation of wetlands.

**Figure 1-1 Photograph of a Freshwater Tidal Wetland** *Courtesy AECOM*

A number of evaluations on the acceptability of different remedial strategies for contaminated subaqueous sediment have been conducted or are underway (e.g., USEPA, 1994; USEPA, 2004; Interstate Technology and Resource Council [ITRC], 2013). Standard remedial approaches generally include: removal, containment, *in situ* treatment, ex situ treatment, and monitored natural recovery (MNR). These technologies may be applicable to the remediation of wetland hydric soils; however the benefits and limitations in wetland systems may differ from those in subaqueous sediment. Table 1-1 presents a summary of remedial options, conditions conducive for their adaptation to remediating wetlands hydric soils, benefits, and limitations for each technology. Distinctions between (1) removal and disposal scenarios and (2) removal, ex situ treatment and disposal scenarios are important because on-site handling of material prior to disposal can have a large impact on the project footprint. On-Site ex situ treatment of excavated hydric soils may require additional laydown, haul road, and staging areas that may not be required for the removal and offsite disposal scenarios, especially if

removed soil is directly off-loaded for transport. The benefits and limitations may differ somewhat according to site-specific conditions. For example, hydric soil removal and off-site disposal may not be readily implementable or desirable at remote DoD locations, but may be of benefit to air safety when coupled with mitigation banking on airport properties.

Remediation of contaminated wetlands has often involved either MNR or no further action (von Stakelberg et al, 2008). However, when the potential for risks associated with exposures to hydric soils have necessitated remedial action, excavation of hydric soils and off-site transport of excavated materials for treatment and disposal has often been a preferred remedy. Currently, this is still the preferred remedial alternative at wetland sites that require cleanup at DoD installations throughout the country. This form of remediation is both destructive to hydric soil structure and habitat and is expensive. In addition, the majority of contaminated wetland areas where excavation is the primary response action will require post-excavation mitigation to return wetland function and ecosystem services, which further increases costs. Wetland restoration efforts following excavation can be expensive and successful restoration is challenging at best (Kusler, 2006a, 2006b). Because of the risk reduction and restoration challenges posed by aggressive remedies, lower impact alternatives that take advantage of or enhance natural recovery processes are actively being tested and demonstrated, as presented by Patmont et al. (2013), Ghosh et al. (2011), and briefly described in Section 2 of this FGM.

When remedial response actions in sensitive ecological systems are contemplated, it is important to balance the potential risks associated with chemical stressor exposure and wetland habitat alteration. As described in U.S. EPA's *2005 Contaminated Sediments Guidance for Remediation of Hazardous Waste Sites*, Executive Order 11990 (1977) promotes the avoidance by federal agencies, to the extent possible, of the adverse impacts associated with the destruction or loss of wetlands if a practical alternative exists. This concern has been explicitly recognized by USEPA since the mid to late 1990's. The Office of Solid Waste and Emergency Response (OSWER) Directive 9280.0-03, *Considering Wetlands at CERCLA Sites* (U.S. EPA 1994), contains further guidance on addressing this Executive Order. U.S. EPA Ecological Risk Assessment Guidance (1999) states that "even though an ecological risk assessment may demonstrate that adverse ecological effects have occurred or are expected to occur, it may not be in the best interest of the overall environment to actively remediate the site". The selection of MNR or Enhanced Natural Recovery (ENR) remedies may be driven by short term risk considerations (Stern et al., 2004), depending on burial rates and predicted residual concentrations. The application of amendment materials for ENR remedies may be raise important habitat alteration considerations (Chadwick, 2008).

An U.S. EPA Science Advisory Board (USEPA, 1990a) review of relative ecological risks indicated that environmental protection strategies should prioritize remedial options for the greatest overall risk reduction. It was recommended that the relative risks of remedial strategies were considered, particularly as they related to natural ecosystem destruction (USEPA, 1990a). Habitat alteration may result in greater relative risk than environmental contamination. Suter (1993) identifies three categories for ecological (and public health) risk: (1) *de minimis* (i.e., risks that would not require remediation because they are considered trivial), (2) *de manifestis* (i.e., sites that would require remediation for ecological risk unless a compelling case can be made that remediation could conflict with protection of human health, or sites where remediation is clearly required due to human health risk), and (3) intermediate (i.e., risks that fall between *de minimis* and *de manifestis*). Although useful concepts to qualitatively describe categories of risk, the terms "acceptable risk" (*de minimis* and intermediate) and "remediable risk" (intermediate and *de manifestis*) are used here for the purposes of risk communication. Risks in the intermediate category are not always so compelling as to require aggressive remediation, but may require some action, depending on the balancing of a number of site-specific factors, including costs, health risks, and the risks associated with remediation (e.g., habitat destruction). Based on the lack of human health risk from hydric soil exposure at many wetland sites, and the uncertainties associated with ecological risk analyses at these sites, it is likely that many DoD wetland sites fall into the intermediate category of Suter (1993).

The use of innovative *in situ* remediation technologies that reduce risk without destroying or functionally altering wetland ecosystems has the potential to result in remediation cost savings with minimal loss of

ecological function and therefore, these technologies could serve as viable alternatives for the management of wetland sites with intermediate risk level. *In situ* remediation technologies applied to wetlands and as discussed in this FGM may be considered an ENR remedy that ideally includes a long term monitoring component, or Enhanced Monitored Natural Recovery (EMNR). In addition, use of *in situ* technologies aligns with a wide variety of federal and state-led green and sustainable remedial approaches (Ghosh et al., 2011). For instance, the federal government is actively pursuing a sustainable approach to all its activities in accordance with Executive Orders 13423 and 13514, and recent guidance documents (Department of Navy [DON] 2012a, 2012b, DoD 2009, USEPA 2008a). Less invasive *in situ* technologies may be deemed more often viable when sustainability metrics are included in remedial decisions.

## 1.2 Management Framework

A management framework was developed for this FGM to assist end-users in evaluating the potential appropriateness of applying *in situ* remediation technologies as an EMNR remedy at a site. The critical steps in selecting, assessing, and implementing *in situ* remediation technologies are shown on Figure 1-2. The process generally follows the chronological development of a project as it moves toward and through *in situ* active remediation. Monitoring often serves as the first and last step (site characterization and long term monitoring) in the process as a site is characterized prior to remedy selection and then remedy effectiveness monitored at construction completion.

The goal of the preliminary amendment selection process is to select an appropriate amendment based upon information available in the literature for *in situ* active remediation. Amendment selection will be based upon the demonstrated sequestration capabilities of an amendment for a specific compound or class of compounds during the laboratory bench scale evaluation step (see Amendment Selection Highlight on next page). Amendment delivery system selection will be based upon application means and methods as well as site hydrological and geotechnical conditions within the remediation footprint.

An evaluation of permitting needs is recommended early in the process. Initiating the permitting applications early in the project will assist with identifying special considerations for the pilot study and remedial design stages. Physical space constraints associated with wetland areas and permit/environmental window restrictions should be identified early in the management process to develop a schedule that achieves project milestones within these constraints. Also, the process of upscaling and adapting a treatment technology for construction based on the outcomes of the pilot study will be streamlined if physical and environmental constraints are well understood.

The means and methods applied in the construction stage will be informed by the outcomes of the preceding management framework steps, including permitting. Design specifications that have incorporated site-specific challenges may be modified based on constructability review, equipment availability, costs and schedule. Modifications to construction design may require additional metrics are considered for construction and long term monitoring.

The objectives of long term monitoring will be site specific but typically will incorporate, at a minimum, monitoring metrics that will be used to adaptively manage the site after construction is completed. Triggers for contingency actions should be identified during planning stages so that maintenance and contingency actions are initiated prior to breakthrough.

**Amendment Selection**

Amendments are chemically active materials used to limit the bioavailability of targeted COCs. Amendments are generally compound- and process-specific, and an understanding of the treatment mechanism is required to optimize selection of the appropriate amendment/contaminant combination. Several mechanisms have been applied to the remediation of contaminated sediments or soils for a wide variety of compounds. Mechanisms researched include adsorption, precipitation, oxidation/reduction, dechlorination, sequestration and/or additional physiochemical processes. At the time of writing this FGM, adsorption has been the primary mechanism employed for *in situ* active remediation.

Adsorptive amendments have been evaluated at length in the laboratory and to a lesser degree in the field at pilot and full scale applications for their ability to limit the bioavailability and mobility of HOCs and metals. Adsorptive remedial agents which are well characterized within the laboratory include activated carbon, apatite, coke, organoclay, zeolites, and zero valent iron (Barth, 2008; Reible, 2004). Three of these amendments (activated carbon, apatite, and organoclay) have been identified as promising amendments for *in situ* wetland remediation and are the focus of discussion presented in this FGM. Information is available in the literature for the other amendments mentioned.

Amendments that are appropriate for *in situ* remediation of wetlands include materials that have the ability to sequester organic or metal contaminants present in the environment. Sequestration agents are typically compound-specific, as some agents have high affinity for sorption of organic contaminants (e.g., organoclays, activated carbon, and other carbon forms), and others for metals (e.g., apatite). This manual identifies reagents that are amenable to sequestering organic contaminants and metals and cites supporting research. As research in this area is extremely active, new studies are continually being produced and published. The user of this manual is encouraged to perform a current literature review prior to finalizing treatment amendments to verify the selected amendment is the best demonstrated technology for the specific COCs at a site in question.

The FGM also provides a framework for developing performance evaluation criteria to determine the success of field application of *in situ* treatment technologies and for evaluation and estimation of costs associated with use of these technologies. The remainder of this document is loosely organized around this framework:

- **Section 2** presents information on site characterization and monitoring that can help inform use of in situ wetland remediation technologies.
- **Section 3** presents a detailed description of in situ remediation technology and general considerations for its use.
- **Section 4** discusses design considerations relative to these technologies.
- **Section 5** presents implementation processes and recommendations.
- **Section 6** discusses post-implementation considerations and long term monitoring.
- **Section 7** includes cost assessment and estimation parameters relative to use of these technologies

**Figure 1-2 Management Framework Process**

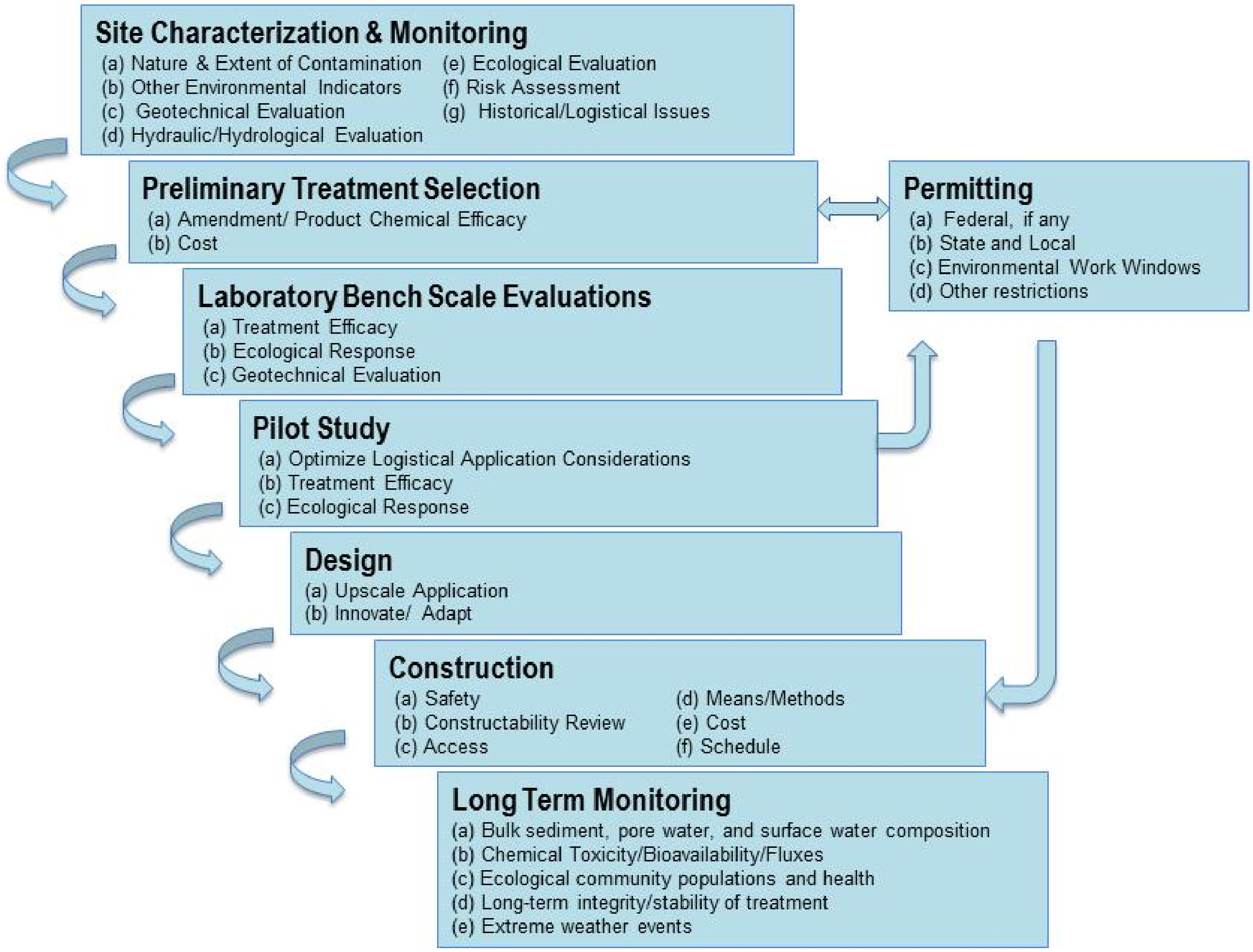


**Table 1-1 Remedial Options Summary for Wetland Hydric Soils**

| Remedial Option | Conducive Conditions | Potential Benefits | Potential Limitations |
|---|---|---|---|
| **Monitored Natural Recovery** | - High value placed on low impact solutions.<br>- Natural sediment deposition occurring.<br>- All significant sources have been identified and controlled.<br>- COC concentrations in biota are naturally moving towards risk-based goals.<br>- Low energy hydrodynamic conditions. | - Low impact solution to the existing ecosystem.<br>- No short term risk from treatment application.<br>- No alterations to<br>- Relatively low cost<br>- Low energy requirements<br>- No disruption to neighboring communities | - Long timeframe to reduce existing risk<br>- Long term monitoring required<br>- Limited assurance of risk reduction (conditions may change)<br>- Limited formal guidance available. |
| ***In Situ* Treatment (through noninvasive application of sequestration amendments (ENR)** | - High value placed on low impact solutions.<br>- All significant sources have been identified and controlled.<br>- Low energy hydrodynamic conditions.<br>- Appropriate risk profile. | - Low impact solution to the existing ecosystem.<br>- Can reduce exposures in Biologically Active Zone (BAZ).<br>- Limited short term risk from treatment application.<br>- Will not significantly alter soil elevations or hydrology.<br>- Relatively low cost<br>- Low energy requirements | - Limited long-term demonstration of technology.<br>- Technology applicable to a limited number of COCs.<br>- Institutional controls and long term monitoring may be required. |
| **Containment**<br>**(e.g. thin layer cap, isolation cap)** | - Low energy hydrodynamic conditions.<br>- Elevation changes will not affect hydrology or flood elevation of site.<br>- Anticipated future site use is compatible with cap. | - Can quickly reduce exposure.<br>- Limited short term risk from treatment application.<br>- Relatively inexpensive.<br>- Established practice, with established formal guidance. | - Possible impacts to ecosystems during treatment application.<br>- Long term monitoring /maintenance required.<br>- Will alter elevations possibly affecting site hydrology.<br>- Institutional controls and long term monitoring may be required |
| **Removal**<br>**(e.g. excavation, dredging)** | - Contaminated hydric soil underlain by clean soil.<br>- Limited incidence of hardpan, bedrock, debris<br>- Discrete areas of high COC concentrations.<br>- Site layout accommodating for material transport off site[1]. | - Permanently removes contaminant from the environment.<br>- Does not reduce flood control capacity.<br>- Limited monitoring requirements following treatment.<br>- Well established practice, with established formal guidance. | - Large impact to ecosystem at time of treatment.<br>- Invasive species concerns.<br>- Difficult to replace hydric soils in kind.<br>- Risk during action and *ex situ* management of materials.<br>- Energy intensive.<br>- May be expensive. |
| **Excavation and *Ex Situ* Treatment/Disposal**<br>**(e.g. solidification, stabilization)** | - Limited incidence of hardpan, bedrock, debris<br>- Discrete areas of high COC concentrations.<br>- Site layout accommodating for material handling and treatment[1]. | - Can quickly reduce risk.<br>- Permanently removes and sequesters contaminant from the environment.<br>- Established practice, with established formal guidance.<br>- Treated soil potentially may be beneficially reused | - Requires double handling of soils to remove, treat, and place<br>- Large impact to ecosystem at time of excavation and treatment.<br>- Limited demonstration of technology in wetlands.<br>- Technology applicable to a limited number of COCs. |

Note: [1]Limitations such as site laydown area and sensitivity of the wetland system can have an impact on project footprint and additional considerations may be necessary.

# 2.0 Site Characterization and Monitoring

The first step to evaluate the potential use of an active *in situ* treatment for the remediation of a wetland is to gather and review site characterization data. *In situ* remediation requires comprehensive characterizations of site conditions including geochemical, ecological, hydrological/ hydraulic, geotechnical, and logistical considerations. At many sites, the remedial characterization activities described in this section will have already been completed during early stages of the Remedial Investigation (RI)/Feasibility Study (FS) process. However, it is possible that data gaps may remain at certain sites and additional characterization may be needed for remedy design and baseline monitoring. This section describes the potential characterization information that may be useful, recognizing that existing data may be available to support the engineering evaluation.

Site characterization data provides the critical parameters that will be used in the design of treatment for a site. Additionally, it provides baseline data against which the treatment efficacy can be evaluated. Table 2-1 presents a list of suggested baseline site characterization parameters which are described in further detail in the following sub-sections and may be incorporated into a remedial action plan. While an effort has been made to compile a comprehensive list of critical parameters, there is no substitute for sound engineering judgment and practice. Site conditions may vary widely and evaluation beyond the metrics presented herein may be necessary to adequately characterize and monitor the site.

## 2.1 Nature and Extent of Contamination

The nature and extent of contamination is an important factor in determining if *in situ* remediation is an appropriate strategy for a wetland site. Several design criteria are based upon comprehensive contamination evaluations including the selection of an appropriate sequestration agent; determining application rates; and evaluating risk reduction after application.

A comprehensive understanding of the COC chemistry is important because *in situ* wetland technology mechanisms are designed to treat specific identified contaminants. Amendments are selected based upon chemical characteristics and then designed into sequestration treatments. Inappropriate amendment selection and/or improper chemical characterization at the area of concern may result in limited treatment or unintended negative consequences. Similarly, the spatial distribution of the contamination is also an important parameter. *In situ* wetland remediation is intended for surface applications within the biologically active zone (BAZ) to limit uptake by the local benthos (Ghosh et al, 2011). For this reason, concentrations within the BAZ are the most critical to evaluating bioavailability. COC concentration at depth may also be deemed important in certain scenarios (e.g., upwelling ground water) and should be considered depending upon site-specific parameters. Finally, contaminant concentrations can be evaluated within several phases within the wetland system.

Concentrations within the bulk hydric soil phase are traditionally the first matrix evaluated to assess the presence or absence of impacts. Bulk phase concentrations should be measured to evaluate the total level of contamination within a wetland. Modeling based upon bulk data concentrations may also help to provide a more complete understanding of wetland chemical processes; however, bulk concentrations by themselves are often not sufficient to evaluate if *in situ* remediation is an appropriate technology for a wetland. For instance, for bioaccumulative COCs, treatment efficacy must be demonstrated directly through measurements requiring the evaluation of COCs within the pore water and/or receptor tissue phase because these asses the bioavailability of the COCs (e.g. Werner et al, 2010; ITRC, 2011). An inclusive discussion of evaluating bioavailability can be found in “Incorporating Bioavailability Considerations into the Evaluation of Contaminated Sediment Sites” (ITRC, 2011).

Similarly, toxicity measurements may be used to assess treatment efficacy for nonbioaccumulative COCs (USEPA, 1994a). Acute and long-term lethal or sublethal contaminant effects on organisms may be appropriate end points to assess the nature and extent of contamination, as well as to monitor remedy effectiveness. Depending on the COCs, growth, reproduction or tetratogenic effects may be useful end points (USEPA, 1994a). Criteria for the selection of appropriate toxicity tests for freshwater environments recommended by U.S. EPA include but are not limited to: contact with sediment,

organismal geographic distribution, laboratory culture, ecological importance, physiochemical tolerance, relative sensitivity, and factors such as field validation and peer review (USEPA, 1994b).

**Table 2-1 Typical Site Characterization and Monitoring Parameters**

| Characterization Objective | Parameters |
|---|---|
| **Nature and Extent of Contamination to determine remedial footprint and select appropriate amendment** | Measure contaminant concentrations in potentially affected media (surface soil, subsurface soil, water column, pore water, tissue)<br>Identify compounds of concern for further screening/evaluation<br>Assess the spatial distribution (horizontal aerial/ vertical profile)<br>Assess sedimentation and burial by radiogenic dating |
| **Other Environmental Indicators to understand existing conditions that may affect contaminant fate and sequestration success** | pH<br>Oxidation-Reduction Potential (ORP)<br>Salinity<br>Total Organic Carbon (TOC)/Dissolved Organic Carbon (DOC), Black (Soot) Carbon<br>Moisture Content<br>Turbidity and suspended solids<br>Water Column Properties<br>Visual surface sediment characteristics, bioturbation/oxidation depths, presence of gas bubbles |
| **Geotechnical Considerations to evaluate stability and access for placement** | Soil Permeability<br>Soil Bulk Density<br>Grain Size<br>Moisture Content |
| **Hydraulic and Hydrological Considerations to evaluate stability and existing conditions that may affect contaminant fate and sequestration success** | Surface Water Depth<br>Sediment Stability<br>Groundwater Interactions<br>Tidal Influence<br>Flood / Storm Surge Elevations |
| **Ecological Considerations for baseline and long-term monitoring design** | Threatened/Endangered Species<br>Plant and Animal Diversity<br>Population Studies<br>Habitat Type and Quality<br>Environmental Restrictions/ Work Windows<br>Sediment profile camera studies- characterize recolonization, polychaete population density |
| **Human Health and Ecological Risk Assessment to determine remedial footprint and potential treatment risk reductions** | Benthic community analysis<br>Toxicity testing (laboratory or in-situ measurements)<br>Tissue sampling- measure bioaccumulation, model trophic transfer potential, and estimate food web effects (laboratory or field-collected data)<br>Risk Level |
| **Site Historical and Logistical Considerations to determine site laydown areas, access/egress points, and cultural requirements for remedial construction and permitting** | Geographic Location<br>Site Access<br>Utilities<br>Cultural Considerations<br>Site History<br>Health and Safety |

Table 2-2 presents examples of methodologies that may be considered in the selection and design of *in situ* active remediation. The testing protocols should be selected based upon site-specific conditions and regulatory requirements but methods outside of these requirements may provide useful information for designing the remedial footprint and selecting an appropriate treatment type. Sampling methods found in guidance documents and emerging methods are summarized for the identified matrices. The importance of these methods relative to evaluating applicability and performance of adsorptive or sequestering remediation technologies are discussed in the context of the timeframe during which this FGM was written.

**Table 2-2 Typical Nature and Extent Measurement Parameters to Determine Remedial Footprint and Select Appropriate Amendment**

| Nature and Extent of Contamination | Example Methodologies and Studies |
|---|---|
| **Bulk Hydric Soil** | Standard Methods: Surface Grab Samples/Cores<br>- Assessment and Remediation of Contaminated Sediments (ARCS) Guidance Document (USEPA, 1994b)<br>- Surface-Sediment Sampling Technologies (Schumacher, 2003) |
| **Pore Water** | Established Methods:<br>- Ex Situ Extraction - Centrifugation (USEPA 2001b)<br>- In Situ Extraction – Suction Devices (USEPA 2001b)<br>- Solid Phase Microextraction (SPME) Direct Extraction (Analytical) – (ASTM, 2011)<br><br>Emerging Methods:<br>- Ex Situ Passive – polyoxymethylene (POM) (Hawthorne, 2011)<br>- In Situ Passive – SemiPermeable Membrane Devices (SPMDs) (USEPA 2006); polyethylene devices (PEDs) (Gschwend, 2010); diffusive gradients in thin films (DGTs) (USEPA,2006), Peepers(ITRC, 2004)<br><br>▪ see also ITRC (2011) Appendix C-T2 and USEPA, 2012 |
| **ToxicityTesting and Bioassays** | - Freshwater Benthic Invertebrates – acute and chronic sediment tests (ASTM, 2005; USEPA, 2000a)<br>- Marine Benthic Invertebrates – acute and chronic sediment tests (USEPA/USACE, 1991; USEPA, 1994; USEPA, 2001; ASTM, 2007)<br>- Amphibians – acute sediment test (ASTM, 2007a)<br><br>- see also USEPA(2007) sediment toxicity identification evaluation (TIE) methods<br>- see also ITRC (2011) Appendix C-T3 freshwater sediment toxicity testing and pore-water and elutriate tests |
| **Tissue** | - Overview of Field and Laboratory Tissue Approaches (USEPA, 2000b)<br>- Laboratory Methods for Generating Freshwater and Marine Benthic Invertebrate Tissue (USEPA/USACE, 1991; USEPA, 2000; ASTM, 2008; ASTM, 2010)<br>- Fish Tissue Collection (USEPA, 200c; USEPA, 2008a)<br><br>▪ see also ITRC (2011) Appendix C-T2 |

### 2.1.1 Bulk Hydric Soil

**Figure 2-1 Bulk Soil Sampling**

Bulk soil concentrations are the total concentration of a compound associated with the solid, colloidal and liquid phases of a collected sediment sample. Bulk hydric soil concentrations are typically reported in mass of compound per mass of sediment (dry weight). These concentration data are applicable for evaluation of site data against established regulatory screening values for the relative risk classification of soils or sediments. As of the publication of this FGM, numerous consensus screening values for sediments (sub-aqueous) and terrestrial soils exist, but few if any benchmark or regulatory screening values exist for evaluation of wetland hydric soils. Bulk soil concentrations will help determine if *in situ* remediation is an appropriate technology for the remediation of a wetland site, but may not directly affect the design of the treatment, especially if remediation design is bioavailability driven. However, bulk soil concentrations that are exceptionally elevated (i.e. raw product) may require more intensive remediation strategies than *in situ* treatment. Likewise, lower/background concentrations may not require treatment.

Methods for the collection of hydric soils generally include surface grab sampling (e.g. Figure 2-1) as well as sampling cores to establish concentrations both spatially across the surface as well as vertically. Both sampling techniques are well established protocols in federal and state guidance documents (e.g. USEPA, 2005). As discussed previously, bulk hydric soil concentrations are not a reliable indication of the bioavailable fraction of many COCs and alone may not be an adequate measure of performance.

### 2.1.2 Pore Water

**Figure 2-2 *In situ* Pore Water Sampler**
*Courtesy EA Engineering, Science, and Technology, Inc.*

Pore water concentrations are the concentration of aqueous compound in the interstitial water of a sediment or hydric soil sample. These concentrations are typically much lower than those within the bulk hydric soil matrix and are generally reported as mass of aqueous compound per volume (typically liter) of interstitial water. Pore water concentrations may be compared to established water quality regulatory values to screen for potential risk (Burton, 1998). Recent work has determined that pore water can be an accurate indicator of the bioavailability of PBT compounds (Hawthorne, 2007; Luoma, 1989; DiToro, 2008). Pore water concentrations are a key design parameter for *in situ* remediation technologies. Identification of COCs within the pore water is required to select *in situ* amendments that can treat the dissolved phase. The degree to which contaminants are unbound to organic carbon and bioavailable is a metric that should be monitored post-construction to assess treatment success and to monitor for potential breakthrough. Amendment selection considerations for treating the dissolved phase are discussed further in Section 4.0.

Several advancements have been made in the past decade with respect to sampling and measuring pore water chemistry (e.g. USEPA, 2013, Hawthorne et al., 2010, Gschwend, 2010). Pore water concentrations have historically been evaluated by *ex situ* direct sampling techniques such as collecting sediment samples and expressing the pore water from the sediment matrix (via centrifugation, pressing or filtration). These methods require large sample volumes and have been found to overestimate the concentration of bioavailable aqueous concentrations (Adams, 2007). In response, passive sampling techniques continued to be developed and improved and provide alternatives to conventional techniques (USEPA, 2012). Currently, passive samplers generally rely on two mechanisms to determine aqueous concentrations either *in situ* or *ex situ* (USEPA, 2001a). Adsorption samplers --

including polyethylene devices (PEDs), solid phase microextraction (SPMEs), and polyoxymethylene (POM) -- rely on known partitioning coefficients between the sampler and analyzed compound to determine aqueous concentrations (see Figure 2-2). Diffusive samplers including peepers, Diffusion Equilibrium in Thin Films (DET), and SemiPermeable Membrane Devices (SPMDs), rely on diffusive flux past a barrier (e.g., permeable dialysis material, gels, mesh) to determine aqueous concentrations (USEPA, 2006). Both of these sampling methods are compound specific and generally equilibrium dependent. Seepage meters or piezometers may also be beneficial to measure flux of groundwater through the soil.

### 2.1.3 Toxicity Testing and Bioassays

Laboratory toxicity test results may be used to help estimate the potential adverse effects of target chemicals on ecological receptors for baseline characterization and may supplement field monitoring evaluations of receptor responses to the addition of an *in situ* active treatment. Toxicity may be a design criterion in situations where the protection of specific organisms are outlined in the Record of Decision (ROD) and should be included as a parameter in the treatability study to ensure treatment does not induce toxicity. Toxicity testing also may be a useful remedial performance metric within the long-term monitoring plan. Common tests include laboratory or *in situ* toxicity testing and bioaccumulation tests with lethal and/or sub-lethal endpoints. It may be useful to conduct a bioassay testing program as part of technology performance evaluation at a site for evaluation of plant (USACE, 2004), invertebrate (USEPA, 2002), and amphibian toxicity (NAVFAC, 2004) under laboratory conditions. Species selection in these tests should reflect site-specific conditions (USEPA, 2007). In addition, PBT contaminant tissue residue analysis could be conducted to monitor trends in sequestration of chemical stressors (ITRC, 2011).

### 2.1.4 Tissue

Measuring tissue concentrations is a direct method of determining the bioavailable fraction of bioaccumulative COCs to which an organism has been exposed. Tissue concentrations may be a component of a site's remediation goals, thereby making tissue a design criterion for bioaccumulative compounds. When measured during the monitoring period, these concentrations will demonstrate treatment efficacy (reduction in bioavailability) and may have regulatory applicability, depending on the site geography and regulatory status. Laboratory studies such as the 28-day *Lumbriculus variegatus* bioaccumulation assay can be used to approximate tissue residues in target organisms within a wetland (USEPA, 2000). If a deep water system hosts finfish, fish tissue residue (whole or fillet, depending on risk pathway) may also be sampled and analyzed following standard procedures found in guidance documents (e.g. USEPA, 2008a). Other wetland biota tissue sampling (e.g. plant, amphibian, bird, or other invertebrate) may be appropriate, depending on the site-specific ecosystem (USEPA, 2008a). Caged fish or invertebrate studies may also be used (Magar et al., 2009).

## 2.2 Other Environmental Indicators

Supplemental analyses may yield supporting lines of evidence as to the nature and extent of contamination, fate and transport of COC, bioavailability or potential toxicity, and whether conditions are appropriate for the application of *in situ* active remediation. A discussion of each of these parameters is beyond the scope of this FGM; however, site-specific COCs will determine which parameters and to what extent hydric soil, pore water, or surface water are analyzed. For example, bioassay test results of metals may be explained by the simultaneously extracted metals /acid volatile sulfides (SEM/AVS) ratio (Di Toro, 1990) or their difference (SEM-AVS) and similarly informed by the total organic carbon (TOC) or fraction black carbon (USEPA, 2005). As with metals, measurements of TOC and black carbon in hydric soil and dissolved organic carbon (DOC) and colloids in pore water may inform bioavailability and toxicity assessments. Other environmental indicators are useful to understand existing conditions that may affect contaminant fate and potential sequestration success.

Other potentially useful environmental indicator metrics and supporting lines of evidence are summarized in Table 2-3.

**Table 2-3Typical Indicator Parameters**

| Metric | Supporting Lines of Evidence |
|---|---|
| **pH** | Inorganic COC mobility; toxicity |
| **Conductivity** | Salinity – Ecological assessment |
| **ORP** | Biologically active zone; fate and transport |
| **Moisture Content** | Hydrologic conditions |
| **TOC** | HOC bioavailability; ecological assessment |
| **SEM-AVS** | Metals bioavailability |
| **DOC** | HOC bioavailability |
| **Black carbon** | HOC bioavailability |
| **Hardness** | Toxicity |
| **Colloids** | Bioavailability |

## 2.3 Geotechnical Considerations

Geotechnical measurements may provide additional site assessment information for applying *in situ* active remediation. A notable difference between using reactive amendments as an EMNR strategy and as a reactive capping technique is that under EMNR, the reactive amendments will be mixed into the existing BAZ. In capping applications, the BAZ is reestablished above the capping layer. This treatment approach causes considerably less loading on the foundation sediment and therefore will mitigate some of the geotechnical concerns traditionally associated with capping. However, the amendment delivery substrate should be sized appropriately to avoid creating physical changes to the BAZ that may potentially result in toxicity or other adverse effects due to grain size effects or alterations of soil permeability.

Geotechnical testing also may be useful to evaluate options for equipment access in wetlands, if required, to facilitate amendment deployment. It may be beneficial to evaluate the shear strength/bearing capacity of the hydric soils to evaluate options for providing stable access into the wetland, if required to facilitate amendment deployment. The method for evaluating the shear strength/bearing capacity will require engineering judgment due to the nature of the hydric soils and site access. Each piece of deployment equipment will have limitations with regard to effective deployment distance. Depending on soil conditions and site access, size and configuration of the wetland, temporary access roads into the wetland may be required. This is especially likely the case for larger scale applications (>5 acres). Additional detail regarding proposed deployment equipment and effective deployment distances is provided in Section 5. Geotechnical properties of the wetland soil provide valuable information for these and other construction considerations. A summary of potentially useful geotechnical properties that the end-user may consider evaluating is presented in Table 2-4.

**Table 2-4 Typical Geotechnical Properties**

| Geotechnical Criteria | Applicable Methods |
|---|---|
| Soil Classification | ASTM D2487 |
| Grain Size Analysis<br>(Sieve and Hydrometer) | ASTM D422/ASHTO T88 |
| Density | ASTM D2937 |
| Shear Strength/Bearing Capacity | California Bearing Ratio (ASTM D1883/ASHTO T193),<br>Consolidated, Undrained (CU) Triaxial Shear with Pore Pressure Measurements (ASTM D4767/ASHTO T 297),<br>Direct Shear (ASTM D 3080/ASHTO T236),<br>Laboratory Vane Shear (ASTM D4648), and/or<br>Unconsolidated-Undrained (UU) Triaxial Compression (ASTM D2850/ASHTO T 296) |

**Note**: Shear Strength/Bearing Capacity method may require engineering judgment

## 2.4 Hydraulic and Hydrological Considerations

Hydrologic and hydraulic conditions, along with soil geotechnical properties, will determine the physical stability of a treatment as well as influence ecological habitat at a site. Hydrodynamic forces that may be considered include surface water velocity, tidal surge and wave impact. Measurement of or estimation via modeling of sediment transport, bathymetry and deposition may be necessary for the final design (e.g. DON, 2007). For example, the potential transport of black carbon into or out of a tidally influenced system by tidal flooding should be accounted for in mass loading calculations to determine how much activated carbon needs to be applied to the remedial footprint for a desired effective dosing (See Final Report, ER-200825). Groundwater/surface water flux across the treatment may be a dominant control of contaminant transport (Winter, 2002) and storm surges, current, ice shear, etc. may cause extreme deposition or scour events. A list of potential testing methods is included in Table 2-5.

**Table 2-5 Typical Hydraulic and Hydrologic Parameters**

| Hydraulic/Hydrological Criteria | Applicable Methods |
|---|---|
| Surface water | Tide cycles, surges, and current velocity<br>Hydrograph Analysis<br>Flood elevation<br>Analytical & Numerical Modeling<br>Direct Measurement |
| Groundwater/Surface Water Interaction<br>(Winter, 2002) | Water Balance<br>Hydrograph Analysis<br>Analytical & Numerical Modeling<br>Direct Measurement |
| Wetland Stability | Sediment erosion/scouring/deposition modeled for storm events<br>Ground-truthing models by sediment cores with radiogenic dating<br>Geophysical survey |

## 2.5 Ecological Monitoring

The *in situ* technologies described in this FGM are targeted as a low impact remediation technique for wetland systems. Therefore, the minimization of impacts to native flora and fauna is likely to be important considerations of the remedial design (e.g., laydown area, access roads, site water usage) and construction implementation (see for example, Figure 2-3). A robust baseline and post-implementation monitoring plan should be developed. Studies should evaluate population and/or diversity of resident species. Particular attention should be paid to any threatened or endangered species present.

**Figure 2-3 Dust from Amendment on Leaves**

Wetland habitats often provide prime habitat for various amphibian species, which play a key ecological role in wetlands. Standardized ecological risk assessment protocols are available to assess plant, invertebrate, and amphibian toxicity (e.g., USEPA, 1989, 1997, 1998; DON 1999a, 1999b, 2001, and 2008; NAVFAC, 2004).

A list of potential characterization and monitoring metrics studies is presented in Table 2-6.

**Table 2-6 Typical Ecological Parameters**

| Subject of Monitoring | Measurement |
|---|---|
| Wetland hydrology | Water depth as function of time for a typical tide cycle |
| Resident plants | Abundance/Density – Number of individual emergent plants per square meter |
| | Diversity |
| | Cover |
| Invasive exotic plants | Presence and number http://www.dnr.state.md.us/invasives/ |
| Invertebrates | Invertebrate community health metrics |
| Amphibians | Number of early life stage (egg masses, larvae) amphibians |
| | Number of adult amphibians (e.g., determined via auditory surveys) |
| Plants, invertebrates, amphibians | Survival and growth in laboratory toxicity testing of hydric soils |
| Lower trophic level biota | Presence and magnitude of bioaccumulative chemical stressors in prey items (e.g., invertebrates, amphibians) that may be consumed by birds and mammals |
| Avian and other vertebrate receptors | Presence and magnitude of bioaccumulative chemical stressors in prey items |

## 2.6 Human Health and Ecological Risk Assessment

Following an assessment of the nature and extent of contamination, an ecological and/or human health risk assessment is often conducted to determine whether potential receptors are at risk of harm due to exposure to site related contaminants. The risk assessment may identify the need for a remedial action and can be used to identify site-specific risk-based cleanup levels.

Although ecological receptors are more likely to be present within a wetland, an assessment of potential risks to humans may be warranted, particularly in recreational areas. State and federal guidance documents for conducting risk assessments are available (e.g., USEPA, 1989, 1997, 1998) and the Navy has also developed risk assessment guidance (DON, 1999a, 1999b, 2001, and 2008). In

addition, NAVFAC published a guidance manual presenting the framework for a tiered amphibian ecological risk assessment protocol that could be used to assess potential risks to amphibians as part of wetland evaluations at DoD sites (NAVFAC, 2004). Typically, the risk assessment will include the development of a conceptual site model (CSM) including the identification of potentially exposed receptors, compilation of the appropriate data, an assessment of potential exposure and toxicity, and a characterization of the potential risks and uncertainties in the process. The risk assessment is often conducted in a tiered manner using readily available information to identify potentially complete exposure pathways at a site and progressing to a more refined risk assessment using site-specific information to evaluate complete exposure pathways.

Information gathered to evaluate the nature and extent of contamination or to characterize ecological receptors may be relevant to the risk assessment process. Additional site-specific community surveys, bioaccumulation sampling, or toxicity testing may also be warranted to support the risk assessment.

## 2.7 Site History and Logistical Considerations

Construction and logistical factors (i.e., feasibility, ease of implementation, and cost) may be the most limiting factors in the evaluation of *in situ* wetland remediation technologies. Examples of how site features may inform the implementation approach is presented in Section 5 of this FGM.

# 3.0 *In Situ* Wetland Remediation Technology Description

For the purpose of this FGM, *in situ* wetland remediation is considered the application of an amendment to the BAZ of a wetland in an effort to chemically isolate identified COCs from the biological community and potential human receptors (Luthy et al., 1997; NRC, 2003; Ghosh et al., 2011; this differs from engineered isolation barriers and thin layer capping (see Reactive Treatment versus Non-reactive Treatment Highlight). A conceptual diagram of the treatment mechanism is provided in Figure 3-1. This remedial strategy was developed to provide a less invasive solution to balance the remediable risk in contaminated wetlands and in a remedial context can be considered a form of EMNR. Conceptually, this strategy includes identification of the COCs, selection of an amendment that will reduce the bioavailability of the identified COCs while minimizing impacts to the existing ecosystem, field application of the amendment, and monitoring of contaminant bioavailability reduction and ecological effects.

Although *in situ* subaqueous sediment and wetland remedial technologies have been successfully field demonstrated at a number of sites in the past decade (e.g., see Patmont et al., 2013), longer-term (i.e., longer than 10 years) studies relative to remedial efficacy are currently lacking. Thompson et al. (2012) identified the greatest needs to promote active *in situ* treatment acceptance by stakeholders as a viable remedy are long-term proof of effectiveness and permanence. Table 3-1, which was adapted from Patmont et al., (2013), presents a summary of completed and ongoing AC and biochar pilot projects, many of which have been conducted in wetland settings.

**Reactive Treatment versus Non-reactive Treatment**
Introducing an amendment to wetland hydric soils has the potential to limit exposure to ecological and/or human receptors by sequestering the bioavailable fraction of COCs. Typically, such treatment involves placement of a significantly thinner treatment layer than conventional subaqueous nonreactive caps or thin layer caps. Therefore, amended hydric soil retains the ecologically important BAZ at the surface and exerts less load on the foundation hydric soil layer than a traditional sand cap. Another advantage of reactive treatment over thicker, conventional sand caps for wetland soils is flood storage; unlike traditional capping, little to no compensatory flood storage is envisioned in most in situ sequestration agent applications.

**Figure 3-1 *In Situ* Wetland Remediation Conceptual Diagram**

(a) Wetland Immediately Following the Application of Sequestration Treatment

(b) Wetland with Dispersed Treatment Limiting Bioavailability of COCs.

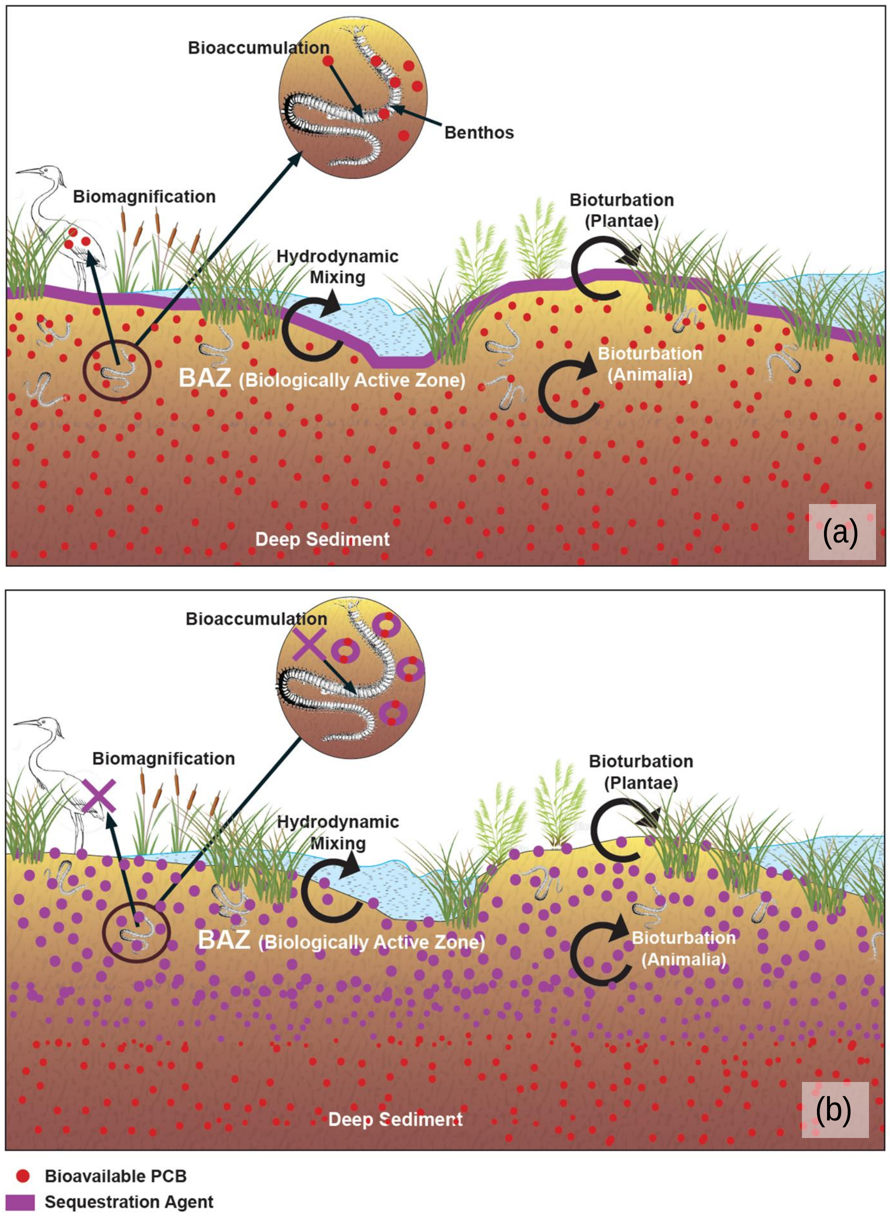


**Table 3-1 Summary of Completed and Ongoing AC and Biochar Pilot Projects**

| Site | Contaminant | Year Initiated | Subaqueous Sediment | Wetland Hydric Soil | Key Findings |
|---|---|---|---|---|---|
| **Completed AC and Biochar Field Pilots** | | | | | |
| Anacostia River, Washington, DC | PAHs | 2004 | X | | Placed coke breeze in geotextile to control long-term mobility |
| Hunters Point, San Francisco Bay, CA | PCBs & PAHs | 2005 | X | | Bioaccumulation reduction with AC mixed into sediment |
| Grasse River, Massena, NY | PCBs | 2006 | X | X | Bioaccumulation reduction with AC mixed into or placed on sediment |
| Trondheim Harbor, Norway | Dioxins/furans | 2006 | X | | Placed AC and capped with sand for erosion protection |
| Spokane River, WA | PCBs | 2006 | X | | Placed full-scale coal-amended cap to control long-term mobility |
| De Veenkampen, Netherlands | Clean sediment | 2009 | X | | Evaluated benthic community effects at different AC doses |
| Grenlandsfjords, Norway | Dioxins/furans | 2009 | X | | Hydraulic application of AC/clay mixture at 100-to 300-foot depths |
| Bailey Creek, VA | PCBs | 2009 | | X | Bioaccumulation reduction with AC placed in freshwater wetland |
| Canal Creek, MD | PCBs & mercury | 2010 | | X | Bioaccumulation reduction with AC placed in freshwater wetland |
| **AC and Biochar Field Studies Underway** | | | | | |
| **Site** | **Contaminant** | **Year Initiated** | **Subaqueous Sediment** | **Wetland Hydric Soil** | **Project Objectives** |
| Onondaga Lake, NY | Chlorinated benzenes & PAHs | 2011 | X | | Evaluate mechanical placement of AC/cap mixtures |
| South River, VA | Mercury | 2011 | X | | Evaluate placement of biochar and bioavailability control in pond |
| Sandefjord Harbor, Norway | PCBs, TBT & PAHs | 2011 | X | | Evaluate placement of AC pellets and bioavailability control in estuary |
| Bergen Harbor, Norway | PCBs and TBT | 2011 | X | | Evaluate effectiveness of AC-amended versus traditional caps |
| Leirvik Sveis Shipyard, Norway | PCBs, TBT & metals | 2012 | X | | Full-scale controlled placement of AC-amended cap |
| Naudodden, Farsund, Norway | PCBs, PAHs, TBT & metals | 2012 | X | | Full-scale placement of layered isolation cap with AC amendment |
| Berry's Creek, NJ | Mercury & PCBs | 2012 | | X | Evaluate bioavailability control in vegetated wetland |
| Puget Sound Naval Shipyard, WA | PCBs & mercury | 2012 | X | | Evaluate placement of AC pellets in under-pier areas |
| Custom Plywood, Fidalgo Bay, WA | Dioxins/furans | 2012 | X | | Evaluate AC and cap effects in sensitive eelgrass environment |
| Duwamish Slip 4, WA | PCBs | 2012 | X | | Full-scale AC-amended cap to control long-term mobility |

Note: This table includes information adapted from Patmont et al., 2013

Similarly, non-reactive containment measures (e.g., thin layer caps [TLC] and isolation caps) have also been investigated as remedial treatment in contaminated wetlands. This remedial strategy differs from *in situ* active remediation in that, depending on thickness, it limits exposure of the BAZ to contaminated hydric soils (TLC) or it isolates the BAZ (isolation cap) using sand as an ENR agent or as an isolation barrier (see Reactive Treatment versus Non-reactive Treatment Highlight). Examples of non-reactive treatments were demonstrated at Soda Lake, Wyoming and Pine Street Canal, Vermont:

- A thin, six to 12 inch (15 to 30 centimeter [cm]) thin layer sand cap was sprayed over 12 acres of wetland at Soda Lake to limit exposure of the ecosystem to non-aqueous phase liquid (NAPL), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs) and metals. A pilot scale demonstration determined that cap construction was feasible based on monitoring outcomes at three and 11 months post-treatment, which found foundation soils were able to support the cap, COCs were physically isolated and organic compounds were not detected within the cap pore water. Biological resources were not affected by the cap application (Thompson *et. al.*, 2004).
- Pine Street Canal is a 21 acre site with open water and wetland shores contaminated with coal tar and some metals. A thick, 24-36 inch (61 to 91 cm), isolation sand cap with geotextile was installed after draining the canal, which included the wetland shores. Operations and maintenance (O&M) has been required since the application of the cap to address coal tar breakout outside the original capped area and address NAPL sheens observed on the surface water. However, the cap has been overall successful in containing contaminants throughout most of the remedial area (USEPA, 2011). No PAHs or metals have exceeded benchmark values as measured from cores recovered from the wetland areas. Wetland restoration efforts have also been successful.

The *in situ* wetland remediation technologies described in this FGM are closely related to *in situ* reactive capping and other ENR practices, and therefore similarities exist between these remedial options in both concept and practice. However, subtle differences do exist. *In situ* active wetland remediation attempts to reduce the bioavailability of PBT and metal compounds in the existing BAZ, whereas reactive capping is designed to create a barrier over the existing subaqueous sediment (or hydric soil in the case of wetlands) to sequester contaminants that are transported to the water column and non-reactive ENR methods operate by providing a clean layer of sand to the BAZ. In addition, a new BAZ is established on top of the cap with time. Benefits and drawbacks exist for both technologies; however, a critical tenant of *in situ* active remediation is to provide a low impact solution that does not result in the temporary destruction of the established BAZ and vegetation.

Following the selection and evaluation of appropriate amendments for the COC, the amendments are applied to the surface of the hydric soil within the designed remedial footprint. Natural mixing forces (bioturbation and hydrodynamic forces) are the primary vector for delivery of the amendment into the BAZ, limiting the bioavailability of the COCs to the local benthos.

The reduction in contaminant bioavailability (including PBT compounds) within a wetland BAZ is the primary objective of low impact *in situ* active remediation approaches (see Figure 2-1). Therefore, a brief description of chemical bioavailability is included in this FGM to assist the end-user's understanding of how *in situ* active remediation may reduce exposure and risk; a more exhaustive description can be found in the literature (NRC, 2003; Semple, 2003; ITRC, 2011). The referenced literature on bioavailability and *in situ* active remediation is largely based on COCs in sub-aqueous sediments (e.g. ITRC, 2011; Thompson et al., 2012; Patmont et al., 2013); however, the concepts and principles are generally transferrable to hydric soils, with the acknowledgement that specific wetland environmental conditions may differ from subaqueous sediment beds (e.g., moisture content, oxidation-reduction potential, temperature, dissolved oxygen) and as such, have the potential to effect bioaccumulation mechanisms relevant to specific COCs.

Contaminant concentrations are often measured in several matrices in the assessment of contaminated wetlands. Concentrations can be measured within the bulk hydric soil phase, within the interstitial water contained in the hydric soil (pore water), and within tissue of plant, vertebrate, or invertebrate organisms exposed to the hydric soil. Research has shown that bulk concentrations alone are generally inadequate predictors of bioavailability due to complex geochemical interactions within the

bulk matrix for both organic and inorganic COCs (Ghosh, 2000; Jonker, 2004; Ankley, 1994). Procedures have been developed to derive the bioavailable fraction from bulk phase concentrations with mixed results depending upon the nature of the contaminant (e.g., Burgess, 2008; Di Toro et. al. 2005b). For example, bioavailable cationic metals concentrations within reduced sediments are highly correlated with acid volatile sulfides (Di Toro, 2008). However, under oxygenated conditions the controlling factors are less well defined. Similarly, oxyanions under either reduced on oxygenated conditions, have limited predictive models. The bioavailability of HOCs is strongly correlated with organic carbon content within the bulk phase (Ghosh, 2000; Talley, 2002; Jonker, 2004). However, due to the many forms of organic carbon that are typically present within bulk sediment, equilibration-based predictive models based on organic carbon partition coefficient ($K_{oc}$) values have generally led to inaccurate predictions that frequently overestimate the bioavailable fraction. For this reason a more complete understanding of COC concentrations within three matrices (bulk hydric soil, pore water, and tissue) is desirable to adequately characterize the mobility and bioavailability of these compounds in the environment.

## 3.1 General Considerations of *In Situ* Wetland Remediation

General considerations are those site conditions that project managers may need to know to be able to evaluate the application of *in situ* wetland remediation technology in the FS process. Two wetland-specific factors are fundamental to the evaluation process: the type of wetland system (classification) and hydric soil characteristics. These two factors are described below.

### Wetland Classification

In order to describe and better understand wetland systems that are under consideration for *in situ* remedial approaches, this FGM recommends use of a wetland classification system such as the "Wetland and Deepwater Classification System" developed by the U.S. Geological Survey (USGS; Cowardin et al., 1979) The Cowardin classification system provides a framework for inventorying of wetlands and deepwater habitats of the United States, and was developed to describe ecological taxa, arrange them in a system useful to resource managers, furnish units for mapping, and provide uniformity of concepts and terms. The Cowardin system also includes deepwater habitats -- ecologically related areas of deep water, traditionally not considered wetlands.

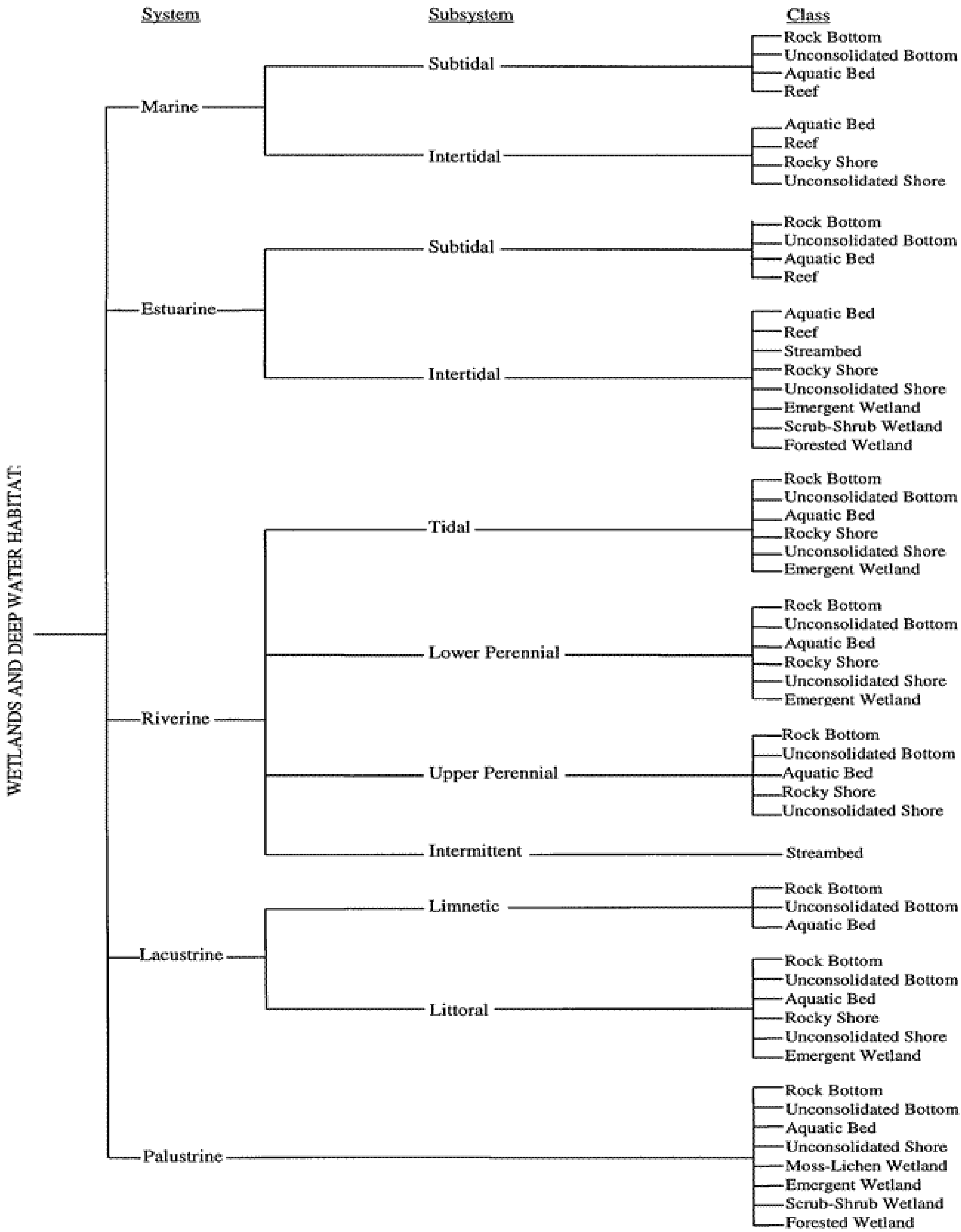
The highest level of classification within this method is the "System", which is defined by hydrological, geomorphic, chemical, and biological factors. There are five systems including: marine, estuarine, riverine, lacustrine, and palustrine, of which wetlands exist in the latter four. Furthermore, each system is divided into subsystems, classes, subclasses, and dominance types. Figure 3-2 shows the complete organizational structure of this classification system.

Wetland classification is a good primary indicator in determining the appropriateness of an *in situ* active remediation strategy. For instance, the efficacy of certain remedial strategies may be more uncertain if the factors influencing biogeochemical processes regulating fate and transport within the wetlands are not understood (e.g., grain size, native organic carbon fraction, mineral vs. organic soil, etc,). Understanding the classification of the system can provide a primary idea of important factors such as salinity, hydrology, organism, and vegetative presence. In addition, it can be envisioned that different wetland structural components may present unique challenges relative to amendment delivery systems - what may be implementable in a palustrine emergent marsh, for instance, may pose significant challenges in a more structurally diverse scrub-shrub or forested wetland.

Understanding the type of wetland system (e.g., palustrine vs. lacustrine) can provide information on key characteristics of the system including erosive capacity, net sedimentation, number and type of organisms present, and hydrologic conditions. These factors will influence treatment mixing, stability and potentially influence efficacy. For example, the hydrologic conditions of a wetland (submerged, inundated, or saturated) will determine whether hydrodynamic mixing of the amendment into the soil may operate or if a weighting agent is required to keep the treatment in place. The wetland type will also determine the types of benthic organisms and vegetation that serve both asbioturbators and COC receptors to be monitored. Thus, the ability of the treatment to get incorporated into the BAZ and the

efficacy and the stability of the treatment(s) may vary with wetland type. Monitoring and maintenance plans, as well as health and safety plans, will also need to be adapted to address specific wetland type conditions.

**Figure 3-2 USGS "Wetland and Deepwater Classification System" (Cowardin, 1979)**



This guidance manual was informed based upon recent work conducted in an emergent wetland within an intertidal estuarine system (See Final Report, ER-200825). This *in situ* active remediation technology was designed as a low impact solution for wetlands and is therefore most readily applied on vegetated nearshore environments within intertidal, perennial, and littoral systems (i.e., not reefs, rocky shores, or rocky bottom wetlands). However, this remedial approach may be applicable to all classes of wetland systems for sites where treatments can be permanently physically integrated into the BAZ to provide low impact solutions.

### Characteristics of Hydric Soils

The end-user of this manual is referred to the 2010 NRCS manual (accessed at http://soils.usda.gov/use/hydric) to determine whether hydric soils (components or morphologies) are within the remedial footprint. The presence or absence of hydric soils and associated hydrologic conditions are also recommended for the preliminary site-specific assessment of the viability of active *in situ* treatment as a potential remedy technology. Additionally, understanding the site-specific hydric soil development and hydrology will help the end-user assess whether the application of active *in situ* treatment might be appropriate under current and future conditions (for instance, if climate change and sea level rise is a consideration).

The field indicators that are used, in conjunction with the formal definition presented previously, to identify hydric soils are presented in *Field Indicators of Hydric Soils in the United States* (NRCS, 2010). Field indicators in wetland soils are formed predominantly by the accumulation or loss of iron, manganese, sulfur, or carbon compounds in a saturated and anaerobic environment. NRCS routinely updates and modifies field indicators as research developments advance. Field indicators may vary by soil texture and are region-specific. Furthermore, anthropogenic alterations (e.g., drainage by a ditch or protection by a dike or levee) may change the hydrologic condition but the soil may still classify as hydric due to its formation under unaltered conditions and so not all hydric soils qualify as wetlands. The NRCS manual (2010) provides these suggested observations to assist with understanding whether hydric soils are likely present or absent:

- Observe site landscape features in the context of the surrounding area;
- Compare and contrast attributes of wet and dry sites that are in close proximity to one another;
- Local topographic variations may be more important to soil wetness than the overall landform; and
- Identify and understand how water moves across the site.

Other site-specific considerations related to the hydrology and hydric soil attributes (e.g. flooding, geotechnical properties) are discussed in the Site Characterization chapter of this FGM.

The appropriateness of an amendment for given hydric soil conditions and how the soil conditions may influence design (i.e., deployment approach, monitoring design, and maintenance considerations) can be evaluated by understanding the following three factors:

- **Physical stability of the soil**—the likelihood of transport of the amendment across the site due to flooding, and the ability of bioturbators, vegetation, or hydrodynamic processes to intermix the treatment into the soil.
- **Chemical stability of the soil**—potential impacts on the efficacy of the amendment during alternating periods of wet/dry or oxic/anoxic conditions and how fluctuating conditions may influence maintenance planning or contingency actions.
- **Interference with amendment efficacy and capacity** caused by the accumulation or loss of iron, magnesium, etc. may require design optimization, anticipated maintenance, or contingency planning.

## 3.2 Performance Objectives

Defining applicable performance objectives is a critical component of selecting and designing any environmental remedy. Performance objectives typically are not developed until after a technology has been selected during the Feasibility Study (FS) process by screening to NCP evaluation criteria.

However, developing an understanding of technology performance objectives may enhance and inform the FS screening process. Objectives for *in situ* active remediation of wetlands, as with any remedial process, will depend upon site-specific requirements governed by applicable regulators, site conditions, potentially responsible parties, site abutters and available technology.

This section provides example performance evaluation and confirmation methods and criteria. Defining performance criteria prior to conducting laboratory and field activities can help achieve a successful technology implementation. Tables 3-2 through 3-5 present examples of performance objectives, metrics, and criteria that could be used to design the remedy and evaluate the remedy success where this technology is applied. Categories of performance objectives considered here include:

- Treatment Related Performance Objectives;
- Risk Reduction Related Performance Objectives;
- Ecological Community Health Related Performance Objectives; and,
- Technology Transfer Related Performance Objectives

Treatment related performance objectives identify the chemical and physical objectives which can be measured and evaluated to determine the relative performance of the treatment. Safety and cost performance is also included in this category. Risk related objectives identify direct ecological health effects to specific plant, invertebrate and vertebrate (including amphibian, fish, avian and mammalian) communities. These criteria are most accurately assessed in the field; however, in some cases, laboratory tests maybe more suited to evaluate specific effects of the treatment on these communities. Ecological community health related performance identifies additional broader ecological metrics. Lastly, technology acceptance and transfer objectives outline the importance of transferring the technological success and failures to the greater community.

The performance objectives, metrics, and criteria may also be useful in developing site-specific data quality objectives (DQO) for site characterization and monitoring. Furthermore, the objectives should be re-evaluated after construction and after long term monitoring to reflect on lessons learned, innovations developed, and evaluate remedy performance.

**Table 3-2 Treatment Related Performance Objective, Metrics, Confirmation Methods, and Success Criteria**

| Performance Objectives | Expected Performance Metric | Performance Confirmation Method | Success Criteria |
|---|---|---|---|
| Effective sequestration of contaminants | Contaminants successfully sequestered on amendment material | Compute % decrease in contaminant pore water concentrations in amended hydric soil | Decrease in contaminant pore water concentrations in amended hydric soil to levels below water quality standards or predicted equilibrium partitioning benchmarks |
| Effective reduction of contaminant bioavailability in treated plots | - Bioavailability reduced in treated plots compared to control<br>- Contaminant bioavailability below risk based level | - Compute % decrease in contaminant pore water and tissue concentrations in treated plots and compare to % decrease observed in control plots<br>- Compare contaminant pore water and tissue concentrations to risk based levels | Pore water concentrations significantly lower in amended hydric soils and below risk based levels (e.g., water quality standards that are presumed to be protective of bioaccumulation-related endpoints for contaminants of concern) |
| Technology is sustainable over design life (Longevity) | Contaminants successfully sequestered and bioavailability reduced over long term | Compute the % difference in contaminant pore water and tissue concentrations over time | Pore water and tissue concentrations decrease or remain constant at or below risk based levels over time (i.e., sorption breakthrough is not observed before the end of treatment design life) |
| Homogeneous material application | Homogeneous/consistent sequestration agent coverage over area (both vertical and horizontal) | Evaluate visual observations of application homogeneity and measurements of sequestration agent thickness and areal coverage | - Visual observations indicate homogeneous material application<br>- Sequestration agent thickness even throughout treatment plot and consistent with targeted thickness<br>- Sequestration agents are within the intended treatment plot area, cover the whole plot and are stable |
| Technology is safe | No safety hazard associated with technology implementation | Document safety related observations and incidents in the field | No safety related incidents occur during implementation and materials/equipment are generally deemed safe when standard operating procedures are followed |
| Technology is cost-effective | Comparable to alternative technologies | Cost comparison calculations to be performed | Technology more cost effective than other alternatives for the site and perform at least equal to or better than other technologies |

**Table 3-3 Risk Related Performance Objective, Metrics, Confirmation Methods, and Success Criteria**

| Performance Objectives | Expected Performance Metric | Performance Confirmation Method | Success Criteria |
|---|---|---|---|
| Phytotoxicity tests indicate reduced or no toxicity | Reduced plant uptake or toxicity – no or reduced risk | Compare pre- and post-treatment plant mortality/survival | Reduced plant mortality/increased survival in amended hydric soils |
| Invertebrate toxicity tests indicate reduced or no toxicity | Reduced toxicity – no or reduced risk | Compare pre- and post-treatment invertebrate mortality/survival | Reduced invertebrate mortality/increased survival in amended hydric soils |
| Amphibian toxicity tests indicate reduced or no toxicity | Reduced toxicity – no or reduced risk | Compare pre- and post-treatment amphibian mortality/survival | Reduced amphibian mortality/increased survival in amended hydric soils |
| Field or laboratory bioaccumulation studies indicate no or reduced bioaccumulation (Invertebrates and Vertebrates) | No or reduced bioaccumulation | Compare tissue concentrations of organisms exposed to unamended and amended wetland hydric soil | Tissue concentrations lower (or zero) in organisms exposed to amended hydric soil compared to organisms exposed to unamended hydric soil |

Note: For full-scale implementation, field tissue residue data may often be preferable to laboratory bioaccumulation data

**Table 3-4 Ecological Community Health Related Performance Objective, Metrics, Confirmation Methods, and Success Criteria**

| Performance Objectives | Expected Performance Metric | Performance Confirmation Method | Success Criteria |
|---|---|---|---|
| Wetland hydrology and soil chemistry remain the same after amendment application | Application of amendment does not substantially alter wetland hydrology, surface water dissolved oxygen, or soil oxidation-reduction potential and pH. | Compare hydrological and indicator chemistry conditions prior to and after treatment | Wetland hydrology and soil chemistry not changed by amendment application |
| Resident plants survive amendment application and remain healthy | No substantial change to resident plant community abundance, diversity, and cover associated with application of amendment. Nutrient uptake by wetland vegetation not adversely impacted. | Compare resident plant community abundance, diversity, and cover prior to and after treatment. Monitor nutrient uptake in plant tissue. | Resident plant community abundance, diversity, cover and nutrient uptake not adversely affected by treatment |
| The presence of invasive exotics does not increase after treatment | No increase in invasive exotics due to application of amendment | Monitor the presence and number of invasive exotics; compare pre- and post-treatment conditions | The presence and number of invasive exotics do not increase due to amendment application |
| The invertebrate community survives amendment application and remains healthy | Invertebrate community/population health metrics either increase (if community is at risk from bioavailable chemical stressors) or remain consistent (if no significant community health risk present due to bioavailable chemical stressors prior to application) | Compare invertebrate community/population health metrics prior to and after treatment | No adverse impact to invertebrate community/population health due to amendment application |
| The amphibian community survives amendment application and remains healthy | Numbers of early life stage (egg masses, larvae) and/or adult (via auditory survey) amphibians either remain constant or increase following application | Compare the number of early life stage and/or adult amphibians pre- and post-treatment | The number of early life stage and/or adult amphibians increased or remained constant after amendment application |
| Avian and other vertebrate receptors remain healthy after amendment application | Modeled body weight normalized doses of bioaccumulative chemical stressors in prey items expected to decrease over time (as stressors become less bioavailable), and thereby enhance the well-being of consumers of prey items (e.g., avian receptors). | Monitor bioaccumulative chemical stressors in prey tissue or residues | Bioaccumulative chemical stressors decreased in prey tissue or residues over time resulting in reduced exposure of avian and other vertebrate receptors |

**Table 3-5 Technology Acceptance and Transfer**

| Performance Objectives | Expected Performance Metric | Performance Confirmation Method | Success Criteria |
|---|---|---|---|
| Regulatory acceptance of technology | Technology considered acceptable by state or federal regulatory agency as a remedial alternative. Transfer of project successes, failures, and lessons learned to regulators, practitioners, and other stakeholders. | Selection as the preferred remedy in the FS. Full scale implementations demonstrate long term efficacy and permanence. | Permitting requirements, if any, successfully met. Regulatory agencies accept permitting as an approval of the technology's ability to meet remediation critieria Approval and implementation of full or partial remedy technology at other sites. |
| Community acceptance of technology | Community considers technology acceptable and applicable at other sites as a remedial alternative. | Selection as the preferred remedy in the FS. Full scale implementations demonstrate long term efficacy and permanence. | Applicable permitting requirements successfully met. Stakeholder and community acceptance of technology. Approval and implementation of full or partial remedy at other sites. |
| Technology transfer | Transfer of project successes, failures, and lessons learned to regulators, practitioners, and other stakeholders. | Transfer results to potential end-users via professional conference presentations and posters, stakeholder meetings, permitting agency meetings. | Technology transfers move the technology toward stakeholder acceptance and continuous technology advancement. Presentation of technology in conference or in journal. |

# 4.0 Technology Considerations

Active *in situ* remediation, like all technologies, has advantages and limitations. The following advantages and limitations should be considered by project managers making remedial decisions for wetland sites. The technologies described in this FGM allow targeted *in situ* remediation of hydrophobic organic or metal contaminants in wetland hydric soils without destroying or functionally altering wetland ecosystems and minimizing impacts on ecosystem components. This guidance is primarily applicable to wetland areas with remediable risk requiring some type of non-time critical remedial response. More aggressive remedial alternatives such as excavation are typically very costly. On the other hand, using the current low impact technology could potentially result in significant cost savings. In addition, due to the minimal disturbance caused by this approach, achieving regulatory and stakeholder consensus might be less challenging than in the case of alternatives that are more invasive in nature.

Although a primary goal of this approach is to avoid harming mature wetland communities, it is possible that short-term impacts to the herbaceous community and forbs may occur. Measures that can be taken during implementation to avoid these short-term impacts are described in Section 5 and should be followed whenever possible and impacts should be evaluated as part of the post-application monitoring program. Other potential challenges facing this technology include the long term physical stability of the treatment under a wide variety of climatic and hydrodynamic conditions, differences in sorption behavior due to wetting/drying cycles, implementation related factors such as homogeneous amendment application in uneven terrain, application of sequestration agents in substrates that have limited vehicular access, and other logistical challenges.

Balancing trade-offs between destructive and costly remediation (such as excavation followed by off-site disposal or treatment) with leaving residual contamination in place (such as the *in situ* remediation technology) is potentially a contentious subject. Cost consideration of remedial alternatives should include the potential ecological costs of both contaminant and non-contaminant (i.e., remediation) related effects.

## 4.1 Amendment Selection

Selection of the appropriate amendment type, delivery system, and quantity is critical to project success and will be driven largely by the compound or class of compounds targeted, receptors of concerns (human and ecological), hydrological, and geotechnical conditions.

Amendments are chemically active materials used to limit the bioavailability of targeted COCs by treatment mechanism that are typically compound and process-specific. Therefore, the end user needs to have a good understanding of the treatment mechanism in order to select the appropriate amendment/contaminant combination. The remediation of contaminated hydric soils by reactive treatment includes treatment by absorption, precipitation, oxidation/reduction, dechlorination, sequestration and/or additional physiochemical processes. Currently, adsorption has been the primary mechanism for *in situ* active remediation.

Adsorptive remedial agents that are well characterized within the laboratory and increasingly in pilot studies include activated carbon, apatite, coke, organoclay, zeolites, and zero-valent iron (Barth, 2008; Reible, 2004, Patmont et al., 2013). Activated carbon, apatite and organoclay have been identified as promising amendments for *in situ* remediation of wetland hydric soils and are the focus of discussion within this FGM.

Amendments that are appropriate for *in situ* active remediation of wetlands include materials that have the ability to sequester organic or metal contaminants present in the environment. Sequestration agents typically have a high affinity for sorption of organic contaminants (e.g., organoclays, activated carbon, and other carbon forms), and others for metals (e.g., apatite). This section identifies reagents that are amenable to sequestering organic contaminants and metals and cites supporting research. As research in this area is extremely active, new studies are continually being produced and published. The user of this manual is encouraged to perform a current literature review prior to finalizing the amendment selection process to verify the selected amendment is the best demonstrated technology for the COCs.

### 4.1.1 Activated Carbon

Activated carbon (AC) is an industrially manufactured carbonaceous material that has extremely high surface area per unit mass and is produced from high-temperature-treated coal or biomass feedstock. AC varies widely in both grain size and source material, both of which have an effect on the sorption affinity of the material. The adsorbent has been used widely used in industrial, medical and environmental fields and has been well characterized in the laboratory.

AC is commercially prepared by steaming organic materials at high temperature and pressure in the absence of oxygen. Base materials commonly used include coconut shell, coal (lignite, bituminous or anthracite), or wood. Treatment increases the specific surface area greatly (generally in excess of 500 meters squared per gram [$m^2/g$]). AC is currently available from a number of suppliers in various particle sizes and produced from various base materials. Typical sizes range from powdered products (<200 micrometers [$\mu$m]) to granular application (<840 $\mu$m).

AC has been used as a polishing step in water treatment for decades and as a result is well-characterized. AC utilizes an adsorption process, through surface sorption which is applicable to many contaminants including organic compounds, some metals, chlorine and radon. Environmental investigations have determined that AC is an appropriate amendment for the *in situ* treatment of similar compounds including HOCs and metals (Zimmerman, 2004; Walters, 1984; Hale et al., 2009). Effectiveness of AC in reducing COC bioavailability has been shown to improve with decreasing particle size, is dose dependent, and varies with the degree of mixing and contact time (Ghosh et al., 2011).

To date, AC has been demonstrated in the field to reduce the mobility and bioavailability of PBT compounds at several sites. (Table 3-1; Patmont et al., 2013), is physically stable, and maintains effectiveness for several years (Ghosh et al., 2011). A comprehensive review of completed and ongoing projects by Patmont et al (2013) concludes that *in situ* treatment using AC and biochar rapidly and effectively reduces exposure risks and the technology provides a sustainable remedy with less ecosystem disruption than dredging and capping and at lower costs. Another advantage identified in the review of the case studies is that the technology can be implemented using existing equipment, which also contributes to the sustainability and cost lowering aspects of the technology. No field evaluations have been conducted at this time to evaluate the *in situ* reduction of DDT in a sediment remediation application.

AC has also been demonstrated in the laboratory to adsorb other HOCs such as DDT and other pesticides. Tomaszewski (2007) observed that aqueous DDT concentrations and contaminant uptake in SPMDs were substantially reduced (by up to 83% and 91%, respectively) after one month of amending DDT-contaminated sediments with 3.2% activated carbon. Tomaszewski et al. (2008) also observed reduced DDT bioaccumulation in mussels (84 to 91% reduction).

Table 4-1 is included to provide end-users a quick reference of example case studies in which AC has been used in laboratory and field tests. The examples presented in Table 4-1 may help initiate an understanding of laboratory treatability studies and field pilot scale studies. Although these examples are not comprehensive, they provide a basis for beginning a literature search. A review and understanding of laboratory and bench test outcomes may assist the end-user with assessing site-specific bench test outcomes.

The direct adsorptive efficacy of an amendment to a specific a contaminant is most accurately evaluated through laboratory adsorption isotherm studies. Partitioning data (Kd) is the most abundant and consistent metric to evaluate if a specific amendment is appropriate for the COC; therefore, it is good preliminary data to obtain. Adsorption isotherms will not account for site specific conditions that may affect the treatment performance. Site conditions may include several factors (environmental chemistry, hydraulic conditions, benthic population etc.) which could have a large impact on the treatments performance in the field. These parameters are best evaluated in either laboratory of field demonstration studies depending upon the control and parameters evaluated. Application rates, scale of evaluations and treatment performance for the identified contaminant and matrix are small subset of

the critical parameters required to evaluate and design these treatments; therefore, end-users are urged to consult the literature (e.g. Patmont, et al., 2013) to gain a more complete understanding of these studies.

**Table 4-1 Activated Carbon Reactive Technology**

| Study Description | Evaluated Matrix | Performance | Amendment Application | Source | Description |
|---|---|---|---|---|---|
| | | | **PCBs** | | |
| Isotherm (Freundlich) | Aqueous Solution (9-Congeners) | $K_F = 10^{7.53} – 10^{8.95}$L/kg | n/a | McDonough, 2008 | Direct chemical comparison of adsorption between the amendment and COCs. |
| Lab (Batch) | Pore Water<br>SPMD | 92% Reduction<br>77% Reduction | 3.4% AC by weight | Zimmerman, 2004 | Controlled laboratory comparison. Specific site conditions are expected to affect the adsorption performance. |
| Lab (Biocosm) | Polychaete<br>Amphipod | 87% Reduction<br>75% Reduction | | Millward, 2005 | Controlled laboratory comparison. Specific site conditions are expected to affect the adsorption performance. |
| Field – Pilot Scale | SPMDs<br>Clams<br>Amphipods | 34% - 62% Reduction<br>24% - 53% Reduction<br>≈ 50% Reduction | 3.7% - 4.2% AC by weight | Cho, 2007 | Demonstration of the performance of an amendment in a treatment application. Most accurate demonstration of treatment performance. |
| | | | **PAHs** | | |
| Isotherm (Freundlich) | Aqueous Solution (11-Compounds) | $K_F – 10^{5.38}$-$10^{5.83}$L/kg | n/a | Walters, 1984 | Direct chemical comparison of adsorption between the amendment and COCs. |
| Lab (Batch) | Pore Water<br>SPMD | 84% Reduction<br>83% Reduction | 3.4% AC by weight | Zimmerman, 2004 | Controlled laboratory comparison. Specific site conditions are expected to affect the adsorption performance. |
| Field – Pilot Scale | Pore Water<br>PEDs | 98.7% Reduction | n/a | Gardner, 2006 | Demonstration of the performance of an amendment in a treatment application. Most accurate demonstration of treatment performance. |

n/a = not available

### 4.1.2 Organoclays

Organoclays or organophilic clays are organically modified clays (i.e. bentonite) with a chemically applied quarterly amine surface. Organoclays are currently manufactured through several different

suppliers and may vary in particle size, base clay material and quarterly amine chemical structure, which will affect the adsorption capabilities of various products (Alther, 2002; Knox, 2008). These materials have been used historically in the oil and gas industry, as well as in water treatment, and have been well characterized in the laboratory, incorporated into isolation and reactive caps for subaqueous sediments (e.g., McCormick and Baxter Superfund Site; Blischke, 2010). Furthermore, they have been well characterized in the laboratory. However, they have not been incorporated into applications of the technology to wetlands at the time of writing of this FGM and are presented here as a potential amendment for consideration, depending on site-specific conditions and needs.

Organoclay or organophilic clays are chemically altered clay minerals that are converted from hydrophilic to hydrophobic (Alther, 1995). This process increases the surface area of the base clay material and allows it to adsorb HOCs and other non-aqueous phase liquids. Organoclays are available from various suppliers and may have various particle sizes and chemical structures. These materials are appropriate for the treatment of HOCs.

To date, organoclay has been evaluated in the laboratory and fully implemented in the field as part of capping projects, but limited work has been completed with organoclays as in situ remedial amendments. Results indicate organoclays may effectively reduce the bioavailability of PBT compounds such as PAHs. Organoclays have been used as a treatment remedy within a larger capping project at the McCormick and Baxter Superfund Site, Oregon (Blischke, 2010). Organoclay was applied via two sequestration product applications, a granular blend within the sand cap and a Reactive Core Mat, at NAPL seep locations. As of 2011, all visible discharge of NAPL to the river had been effectively eliminated and COC concentrations in the surface water and pore water within the armoring layer were stable and decreasing, consistently below comparison criteria. (Reible and Lu, 2010). Solid-phase microextraction (SPME) *in situ* passive pore water sampling found no evidence of upward PAH migration through the constructed cap (Oregon Department of Environmental Quality, 2011).

Laboratory research has shown that organoclays effectively sequester PCBs as well as PAHs (Sharma 2008; Knox et al., 2007 and 2008). Sharma found the effectiveness of commercially available organoclays were comparable in effectiveness to activated carbon. Thus, this amendment may hold promise for future applications to wetlands *in situ* treatment. In some cases, organoclays were found to be superior to activated carbon, depending on the specific compound being investigated and the presence of high-DOC pore water. Table 4-2 presents a summary of amendment performance in the laboratory for the end-user’s reference should site conditions potentially warrant the evaluation of this technology.

**Table 4-2 Organoclay Reactive Technology**

| Study Description | Evaluated Matrix | Performance | Amendment Application | Source | Description |
|---|---|---|---|---|---|
| **PCBs** | | | | | |
| Isotherm (Linear) | Aqueous Solution (5 Congeners) | $K_d = 10^{3.89}$-$10^{5.36}$ L/kg | n/a | Sharma, 2008 | Direct chemical comparison of adsorption between the amendment and COCs. |
| **PAHs** | | | | | |
| Isotherm (Linear) | Aqueous Solution (3 Compounds) | $K_d = 10^{3.60}$-$10^{4.86}$ L/kg | n/a | Lee, 2011 | Direct chemical comparison of adsorption between the amendment and COCs. |
| Field (Pilot) | SPMDs | Average 98% Reduction between pre and post treatments | Variable | Sower, 2008 | Demonstration of the performance of an amendment in a treatment application. Most accurate demonstration of treatment performance. |
| **Metals** | | | | | |
| Isotherm (Linear) | Aqueous Solution (9 Metals) | $K_d = 0$-$10^{5.32}$ L/kg | n/a | Knox, 2008 | Direct chemical comparison of adsorption between the amendment and COCs. |

n/a = not available

### 4.1.3 Apatite

Apatite or activated phosphate is a naturally occurring mineral from either geological or biological processes. This material is commercially available and may range in particle size and chemical structure depending upon the supplier. Apatite is appropriate for the treatment of dissolved inorganic compounds in the pore water (Knox et al., 2006).

Apatite (i.e., calcium phosphate compounds) is a potential amendment that could be applied in wetland hydric soils in an attempt to reduce bioavailability of metals. Sources of apatite include rock phosphate that contains mineral apatite (Apatite I) or fish bones (Apatite II) (Knox et al., 2006).

Numerous studies have been published on the use of biological apatite (made from fish bones) to treat groundwater and soils contaminated with metals and radionuclides (Conca et al., 2000 and 2006; Matheson et al., 2002; Wright et al., 2004a and 2004 b). Compounds such as lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), uranium (U), and plutonium (Pu) have been immobilized successfully not just in the laboratory, but also in field applications (Wright et al., 2004a; Conca et al., 2006).

Mineral apatite has been evaluated in many studies as well. Chen et al. (1997a and 1997b) used North Carolina mineral apatite to immobilize Pb, Cd, and Zn that leached from contaminated soils and found that pH had an important role on the removal of certain metals such as Cd and Zn, while Pb removal was not affected. Other researchers investigated mechanisms of phosphate stabilization when treating industrial and/or municipal waste material combustion residues contaminated with divalent metals (Eighmy et al., 1997a, 1997b, and 1998). Most recently, studies have been focusing on the application of apatite in subaqueous systems for the treatment of contaminated sediments. Apatite was one of the amendments tested in the Anacostia River, Washington, D.C., *in situ* sediment capping demonstration project that took place in the spring of 2004 (Melton et al., 2003; Crannell et al., 2004; Reible et al., 2006). The material was successfully deployed. Post-treatment monitoring efforts showed no measurable contaminant migration through the caps (Reible et al., 2006). Thus, this amendment shows promise as an *in situ* technology for wetlands hydric soils. Table 4-3 presents a summary of bench test performance to assist the end-user with evaluating its potential if site conditions warrant.

**Table 4-3 Apatite Reactive Technology**

| Study Description | Evaluated Matrix | Performance | Amendment Application | Source | Description |
|---|---|---|---|---|---|
| **Biological Apatite (Type II)** | | | | | |
| Isotherm (Linear) | Aqueous Solution (9 Metals) | $K_d$: $10^{0.90}$ – $10^{3.63}$ L/kg | n/a | Knox, 2008 | Direct chemical comparison of adsorption between the amendment and COCs. |
| Field-Pilot (Terrestrial PRB) | Alluvial Ground Water (pH = 4.5) | Cd: > 99% Removal<br>Pb: > 99.9% Removal<br>Zn: > 99.9% Removal | permeable reactive barrier | Conca, 2006 | Demonstration of the performance of an amendment in a treatment application. Most accurate demonstration of treatment performance |
| **Mineral Apatite (Type I)** | | | | | |
| Isotherm (Linear) | Aqueous Solution (pH =7.7 for 10 elements) | $K_d$: $10^{1.95}$ – $10^{5.57}$ L/kg | n/a | Crannell, 2004 | Direct chemical comparison of adsorption between the amendment and COCs. |
| Lab (Batch) | Contaminated Soil Leachate (pH = 3 – 12) | Cd: 20%-97.9% Removal<br>Pb: 62.3%-99.9% Removal<br>Zn: 28.6%-98.7% Removal | 2% Apatite per original soil mass | Chen, 1997 | Controlled laboratory comparison. Specific site conditions are expected to affect the adsorption performance. |

n/a = not available

## 4.2 Review of Sequestration Agent Products

Amendments have often been applied as an engineered treatment product or systems in recent *in situ* treatment studies. Examples of these treatment systems include composite particle systems, agglomerated pellets, and engineered blends. At this time, suppliers generally specialize in one technology and can incorporate a number of different amendments into that technology and the product

that delivers the amendment can be sized so that the soil substrate is not substantially altered and the optimal dose is delivered to minimize potentially adverse effects (e.g. ≤4% AC, Kupryianchk et al., 2012). Specific combinations will depend upon the supplier and the technology. The following sequestration products have been demonstrated in wetland and subaqueous applications:

**Composite Particle Systems** (CPS) are composed of amendment laden clay polymer particles with an aggregate core. A typical example of this technology is currently patented by AquaBlok® and marketed under the AquaGate® product line. CPS is designed so that it is weighted to assist in the application of amendments through the water column as well as provide ballast once applied, to resist erosion or displacement from hydraulic energy. To date, CPS are constructed with organoclay and activated carbon amendments and are available on a commercial scale.

**Agglomerated Amendment Pellets** (AAP) are comprised of amendment, weighting agents and an inert binder. An example of this technology is patented by SediMite™. AAP is weighted to assist in the application of amendments through the water column as well as provide ballast once applied, to resist erosion or displacement from hydraulic energy. The binder is also designed to slowly break down over time so that natural bioturbation will mix the fine grain amendments into the BAZ. At this time, AAP has been manufactured with activated carbon and has been applied in pilot scale research sites at multiple locations.

**Engineered Blended Amendments** are generally composed of amendment and inert physical stabilization agent to aid in the deployment and post application physical armoring of the amendment. Engineering blends cover a wide variety of designs and are not patented by any company.

Slurry sprays are the application of an unadulterated amendment in a fluidized media (i.e. water). This delivery technique is best applied to amendments with fine particle sizes. This treatment includes a wide variety of designs that can be applied surficially or injected into sub-surficial layers.

## 4.3 Laboratory Bench Scale Treatability Study

The literature and manufacturer's technical documents can often provide general design parameters adequate to develop a preliminary design. However, due to the lack of established practices and the diverse range in potential site conditions, preliminary laboratory testing is an important step to fill in existing data gaps. Generally, testing should be designed to evaluate if the selected technologies can meet the established performance objectives. Parameters should include evaluating the reduction in bioavailability of identified COCs, the physical stability of a treatment and the ecological effects of a treatment in the environment. Testing should display, confirm and/or compare the effectiveness of a treatment at conditions representative of those observed in the site evaluation.

Batch tests provide a good first evaluation of *in situ* active remediation technologies (Hale et al, 2010; Ghosh et al., 2011). These tests are relatively inexpensive, require limited preparation time and are extremely flexible in design. This combination allows for tests to isolate specific chemical process which are critical to specific design objectives. Two critical design parameters for *in situ* active remediation include the adsorption kinetics and the adsorptive efficacy of a treatment. General values should exist in the literature for the active amendments within any treatment considered for this treatment strategy (e.g. Table 4-1); however, the direct understanding of an amendment's performance within a treatment selection or selected environment is often required. Testing protocols able to determine these parameters are also well established in the literature. Specific procedures may vary slightly to account for a number of parameters important to a specific site (pH, TOC, grain size); however the general framework is provided in EPA 835.1230. Results can be used to evaluate performance as well as provide variables for modeling (Hale et al., 2010; Janssen et al., 2010; Werner et al., 2006; Sun et al., 2009). Established practices are not yet developed for these technologies. Therefore, comprehensive understanding of amendment performance as applied to wetlands hydric soils is evolving; however, project examples have been provided above (e.g. Table 4-1 through 4-3).

As an example of how the treatability study can affect amendment selection, the treatability study work for *In situ Wetland Restoration Demonstration* (ESTCP Project ER-0825, 2009) evaluated a variety of sequestration agents for addressing PCB and DDT contamination in a palustrine wetland complex.

These amendments included activated carbon for sequestration, organoclay (OC) for sequestration, and zero-valent iron (ZVI) for reductive dechlorination (biological and abiotic). The primary objective of the Treatability Study was to determine the most effective amendment agent to be used in the In Situ Field Demonstration for the Canal Creek system, at Aberdeen Proving Ground, Maryland. Effectiveness was determined based upon an evaluation of reductions of PCBs and DDTconcentrations in hydric soil pore water following introduction of amendments and was confirmed by demonstrating reduced contaminant bioavailability in post-treatment laboratory bioaccumulation studies.  The Treatability Study estimated the ultimate potential effectiveness of the *in situ* treatment under ideal laboratory conditions, as site conditions and low-impact delivery methods are expected to achieve less thorough mixing and thus a less effective treatment.

The treatability tests were conducted by adding pelletized AC, OC, or ZVI amendments to Canal Creek hydric soil.  Pelletized AC and OC were added at 3% and 6% (dry weight), and ZVI was added at 5% and 10%.  Figure 4-1 depicts reductions in pore water concentrations of five PCB congeners following amendment addition.  These congeners were the sole quantifiable congeners (i.e., congener peaks that were consistent and in high enough concentrations to quantify) identified following a scan for all 209 congeners.

The Treatability Study results indicated that OC had marginal effectiveness for reducing both PCB and DDx pore water concentrations, addition of ZVI actually resulted in increases in PCB bioavailability and DDx pore water concentrations, and the Pelletized AC amendment significantly reduced PCB and DDx pore water concentrations by 40 to 90%.  Figure 4-2 shows DDx amendment agent percent reductions. Relative to the pelletized AC amendment, there was no significant reduction in PCB bioavailability when the activated carbon concentration was increased from 3% to 6%.  The results of the Treatability Study indicated that amendment with 3% activated carbon by weight was the most appropriate amendment choice for the demonstration (NAVFAC, 2009d).

More applied laboratory tests sacrifice the isolation of specific chemical processes in an attempt to simulate conditions that are more representative of the natural environment in which the treatments will be applied.  Specifically, chemical efficacy can be evaluated in column or microcosm studies.  Column experiments are designed to mimic site conditions and apply real world conditions to the treatment while still in the laboratory.  Microcosms are designed to evaluate the benthic component of the technology including a direct measure of bioaccumulation as well as benthic activity (bioturbation). Ecological community heath can also be evaluated in the laboratory prior to field demonstrations. Toxicity testing and other bioassays can provide information to determine the effect of the treatment addition on identified organisms.  Also, geotechnical laboratory testing may also be of use to provide insight into any hydrological conditions that may be altered as a result of applying the treatment such as permeability.  Table 4-4 reviews metrics that should be considered as part of a laboratory evaluation of *in situ* wetland remediation.

### Table 4-4 Bench Scale Studies

| Performance Objective | Test | Metrics |
|---|---|---|
| Chemical Efficacy | Batch Tests | - Compare different treatment amendments/ sequestration products (partitioning coefficients/ adsorptive kinetics).<br>- Optimize application mass<br>- Evaluate impacts of site specific conditions on treatment efficacy. |
| | Column Studies | -Evaluate fate and transport of COC under site simulated conditions. |
| | Microcosms | - Measure reduction in bioaccumulation due to amendment.<br>- Measure toxicity under laboratory or field conditions<br>- Evaluate mixing of amendment into hydric soil due to bioturbation. |
| Ecological Community | Microcosms | -Toxicity/bioassay studies with target organisms. |

### Figure 4-1 PCB Concentration Percent Reductions by Amendment Type

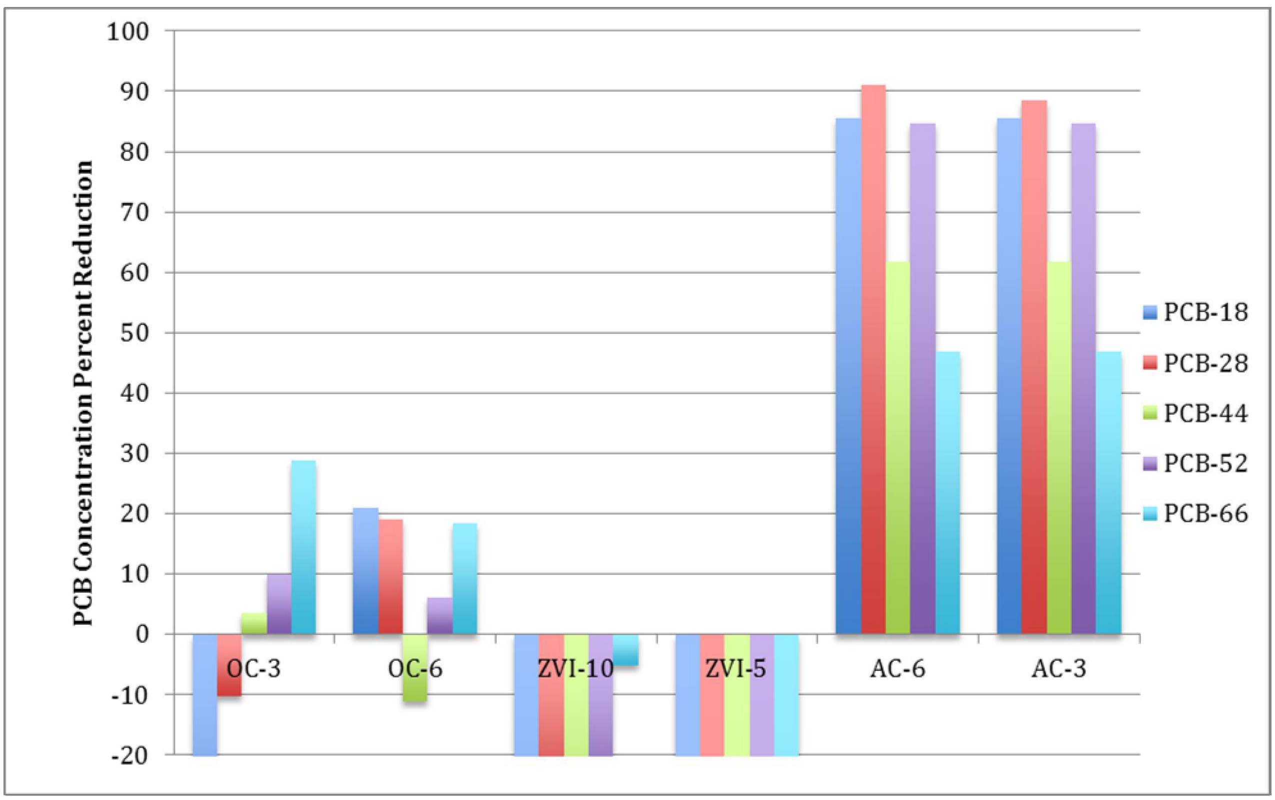
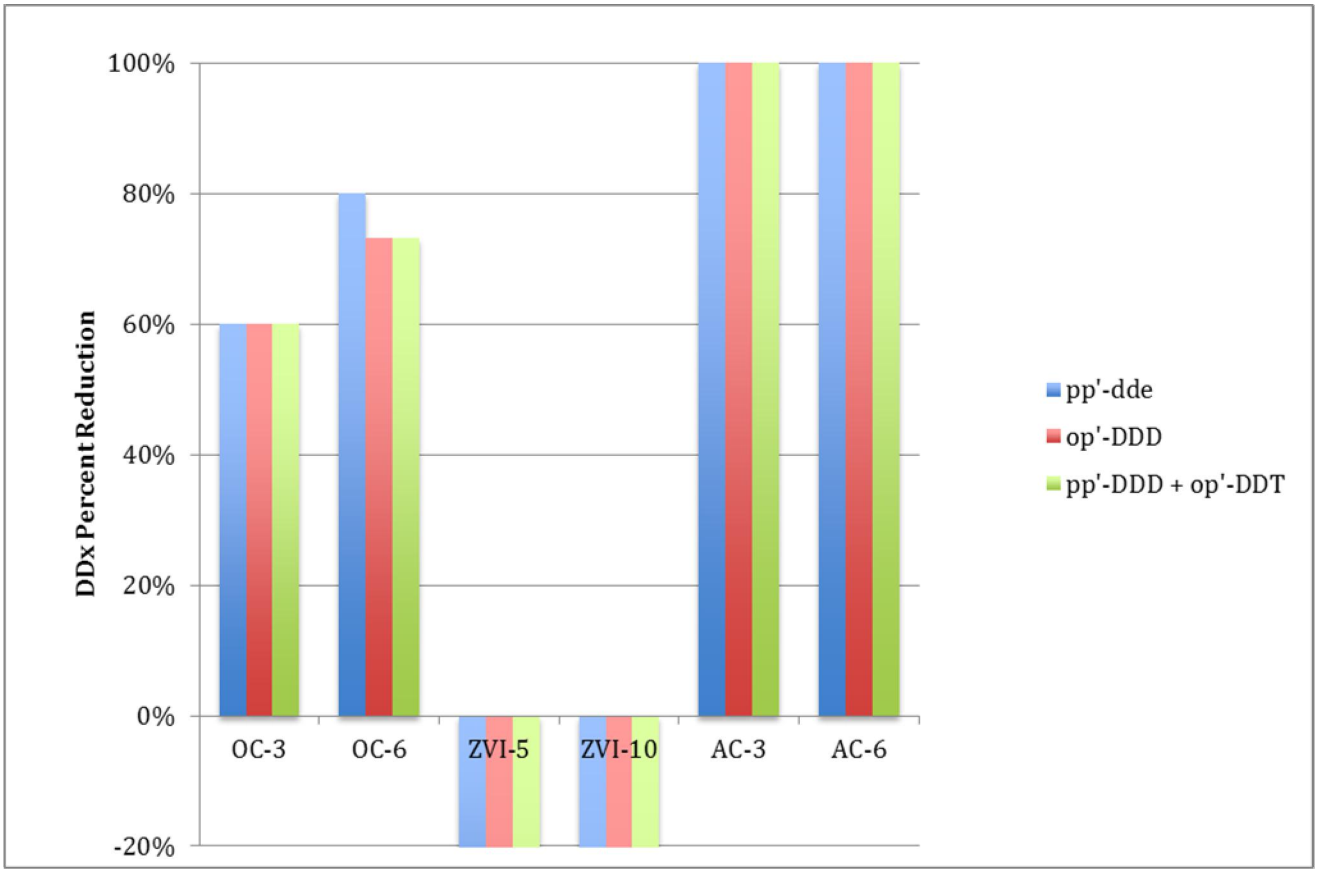


**Figure 4-2 DDx Concentration Percent Reductions by Amendment Type**




## 4.4 Permitting and Relevant Regulations, Laws, and Guidelines

This section addresses federal requirements for working in and around wetland systems. Regulations that may apply to or permits required for using this *in situ* technology in floodplains and wetlands may vary by state and local authority; thus, the review of regulations and permits provided below is limited to the federal level, but the technology end-user should be aware of local and state requirements. The site-specific contaminants of concern and the regulatory auspice(s) under which the remediation is being conducted may also have specific programmatic requirements not addressed by this regulatory review.

Relevant federal regulatory drivers include the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), which authorizes USEPA to clean up contaminated sites and to compel responsible parties to perform cleanups or reimburse the government for EPA-lead cleanups, as well as others described herein.

Other pertinent federal regulations include:

- **Clean Water Act (CWA) Sections 404 and 401** establish performance standards and water quality standards for the discharge of dredged or fill material into U.S. waters that may impact habitat and adversely affect the biological productivity of wetlands/aquatic ecosystems by smothering, by dewatering, by permanently flooding, or by altering substrate elevation or periodicity of water movement.
- **Endangered Species Act (16 United States Code [USC] Chapter 35)** requires determination as to whether such species and its habitat reside within an area where an activity under review by a governmental authority may take place. The technology should be evaluated in this context if such species or habitats are present, as with any technology.

- The **Migratory Bird Treaty Act (Title 16 USC Sections 703-712)** protects migratory birds, their eggs, and nests from actions that may kill or disturb them. Use of *in situ* remedial technologies may have the potential for accidental death or injury of migratory birds during construction activities, depending on seasonality, site-specific habitat, construction approach (schedule aggressiveness, extent of laydown areas, clearing and grubbing activities, etc.). The presence of migratory birds should be determined prior to construction and mitigated against.
- Floodplain development under **Executive Order 11988** (1977) and the protection of wetlands under **Executive Order 11990** (1977) require actions to avoid or minimize long- and short-term adverse impacts associated with the occupancy and modification of floodplains and the destruction or modification of wetlands, respectively. Manual and automated methods of material deployment are typically used to minimize impact to wetland soils and vegetation. A construction approach that incorporates project scale-appropriate contingency plans for unforeseen conditions such equipment failure is most likely to comply with this regulation. These Executive Orders are typically "to be considered," (TBC) rather than ARARs.
- **Fish and Wildlife Coordination Act** (16 USC Chapter 5A) requires that any modification of any stream affected by an authorized action provide adequate protection of fish and wildlife resources.
- **Coastal Zone Management Act** (16 USC Section 145) requires that activities affecting the coastal zone and adjacent shoreline are conducted in manner that is consistent with approved State management programs.
- Federal or state water quality standards may be applicable or relevant and appropriate requirements (ARARs) for determining cleanup levels. Water quality standards may be relevant and appropriate depending on the uses designated by the state, which are based on existing and attainable uses. If supplying drinking water then federal water quality standards are not relevant and appropriate. Notably, as described in *Water Quality Standards for Wetlands National Guidance (*USEPA, 1990b), state water quality criteria may contain narrative criteria that prohibit certain actions or conditions or statements about what is expected (e.g., "aquatic life shall be as it naturally occurs").
- In addition, the federal government is actively pursuing a sustainable approach to all its activities in accordance with **Executive Orders 13423** (2007) and **13514** (2009), and the recent DON (2012a, b) and DoD (2008) guidances. Less invasive *in situ* technologies may be more often considered when sustainability metrics are included in remedial decisions.
- Numerous additional TBC regulations are summarized in *CERCLA Compliance With Other Laws Manual* (USEPA, 1988). Depending on site specific needs, some TBC regulations may be ARARs (e.g. NPDES discharge, RCRA solid waste management).

Several guidance documents provide overarching wetlands and sediment remediation guidance and information on topics closely related to *in situ* active remediation technologies. These include but are not limited to:

- Considering Wetlands at CERCLA Sites (USEPA 1994c),
- Water Quality Standards for Wetlands National Guidance (USEPA, 1990b),
- Contaminated Sediment Remediation Guidance for Hazardous Waste Sites (USEPA, 2005),
- Green Remediation: Incorporating Sustainable Environmental Practices into Remediation of Contaminated Sites (USEPA, 2008b)
- Incorporating Bioavailability Considerations into the Evaluation of Contaminated Sediment Sites (ITRC, 2011),
- Guidance on Green and Sustainable Remediation (DON, 2012),
- Consideration of GSR practices in the Defense Environmental Restoration Program (DoD 2009),

- Sediment Capping Resource for Manufactured Gas Plant Sites (Palermo et al., 2008), and
- User's Guide for Assessing Sediment Transport at Navy Facilities (DON, 2007).

Two DoD In Situ Wetland Restoration field demonstrations projects (ESTCP Project ER-200825: *In Situ Wetland Restoration Demonstration* and ER-200835: *Evaluating the Efficacy of a Low-Impact Delivery System for In Situ Treatment of Sediments Contaminated with Methylmercury and Other Hydrophobic Chemicals*) were recently permitted at the Canal Creek Site, Edgewood Area of Aberdeen Proving Ground, Aberdeen, Maryland. For both of these field demonstration scale projects, the USACE determined that the application of sequestration agents did not constitute placement of fill in a water of the US. The following permits were required for successful execution of these two projects:

- Wetland License for the State of Maryland
- Maryland State Programmatic General Permit-3 Permit Compliance, Self-Certification Form
- Joint Federal/State Application for the Alteration of any Floodplain, Waterway, Tidal or Nontidal Wetland in Maryland
- Local grading and building permits

The timeframe from permit preparation and application to issuance at Canal Creek took approximately 12 months, and included a joint evaluation review by the State of Maryland and the US Army Corps of Engineers. A Joint Federal/State Application for the alteration of any floodplain, waterway, tidal or nontidal wetland in Maryland was required, after which the Maryland Joint Evaluation Meeting was held in regard to Project No. ER-200825. The final step in the process to obtain authorization required to work in tidal wetlands in Maryland was obtaining a Wetlands License for the sediment research project in Canal Creek.

Wetland and other environmental permitting/licensing at non CERCLA sites may take anywhere from less than a few months to a year or more; thus, the permitting process should be understood and initiated, as appropriate, early in the remedy selection process. Implementation in different states and/or at different scales may require a different permitting process and it is recommended that the RPM or other end user check all applicable local, federal, and state guidelines.

# 5.0 Pilot Scale, Design and Full Scale Implementation

At the completion of the bench scale treatability testing, providing that a treatment has performed to an acceptable level, retained treatments are often evaluated in a pilot study. Pilot studies evaluate the logistical applicability of applying the selected treatments as well as monitor their performance in the environment. This section includes a discussion on treatment delivery techniques that are applicable at both a pilot scale and full scale application. .

## 5.1 Health and Safety

As with any field program, health and safety is of paramount importance. Appropriate planning including the preparation of a site-specific Health and Safety Plan will help ensure the employment of appropriate safeguards, means and methods to perform the work activities in such a way to protect workers, the public and the environment. Specific consideration should be given to the following:

- Environmental exposure to impacted media
- Working around heavy construction equipment
- Slip, trip and fall hazards associated with working on soft and/or uneven terrain
- Working in and around waterways
- Falling/projected amendment/debris
- Dust control (from amendment delivery procedure)
- Other site specific considerations

## 5.2 Monitoring Design

Ghosh et al. (2011) provide recommendations in study design to address the challenges in assessing remedy effectiveness due to transient and long-term changes that occur in the natural environment during pilot scale and full scale phases. Ghosh et al. (2011) recommendations include:

1. Observations of changes in bioaccumulation at treatment sites need to be contrasted to ongoing changes at properly selected background control sites.
2. Using deposit-feeding organisms for biomonitoring is preferable to using filter feeders for assessing pilot-scale remediation.
3. In situ assessments should preferably have an ex situ laboratory component to delineate overlying water and depositional impacts.
4. The number of replicate samplings should be large enough to account for spatial variability at the site.
5. Multiple lines of evidence for exposure reduction, including physical, chemical, and biological, need to be pursued to obtain confidence in the observations.

## 5.3 Engineering Design and Contracting

In order for a Remedial Project Manager (RPM) and end-users to move from bench scale calculations to actual design and implementation, several additional analyses are typically warranted.

- Additional evaluation is typically needed to scale from a treatability study application rate to field implementation. Appendix A outlines the general process for calculating AC application rates in the context of hydric soil densities. To transition these calculations to full scale implementation, the following adjustments will be necessary:
  - Site-specific hydric soil physical (e.g., bulk density) and chemical properties (e.g., pH, redox) characterized throughout the footprint;
  - Updating the application area from a pilot study test plot size to the remedial footprint extent;

- Amendment design depth to determine treatment application thickness;
- Note that existing black carbon (BC) concentrations should not be factored into activated carbon application rates; they serve as a baseline.

- Design of site-specific contingency of the AC dosing based on pilot study results to account for potential loss of material during and after application. The loss of material during application can be controlled through measures specific to the method of application and erosion control. For instance, a weighting agent can be used to keep treatment in place and placement of erosion controls such as straw wattles can protect amendments until they are incorporated into the BAZ.
- Construction stage and early post-construction stage sampling and evaluation may be required to ascertain effects treatment has on the wetland system and to determine if natural mixing is occurring as intended. Also, post-placement migration of amendment may occur so more frequent monitoring may be necessary to assess potential migration within the system.
- The application technology used to deploy the selected amendment will be determined by site access, site conditions, project budget, and the form of the amendment (e.g., pelletized or slurried form). Delivery methods are discussed in the next section.

The results of these analyses are typically documented in a Remedial Design Work Plan (or Design Basis Document) which provides justification for the design. The design is typically prepared and evaluated at different pre-determined stages of development including the following:

- Draft design (30-60% design) – provides outline of proposed content with draft construction drawings and specifications (content may not be complete depending on progress of development)
- Draft Final Design (85-90% design) – provides complete draft for stakeholder comment
- Final Design (100% Design) – Includes project stakeholder feedback and is ready for contractor procurement.

For amendment application, construction contracting may best be served by a Performance-Based Application Contract. In such a contract vehicle, the construction contractor is given a target rate of amendment application to the hydric soil surface on a mass or volume basis. Under this scenario, the contract documents should be clear in defining the means by which the measurements for verification will be collected. Other elements of the work can be handled in more traditional methods of measurement and payment (lump sum, unit price, etc.). Amendment application, erosion control, and waste management practices are verified by oversight personnel.

## 5.4 Delivery Methods

Key challenges for the delivery of *in situ* wetland remediation are summarized below:

<u>Accessibility</u> – Given the remote location of some wetland areas, the physical accessibility of the application equipment for the sequestration agents can be challenging. Depending on the size of the area to be treated, the characteristics of the wetland, terrain, vegetative cover, the accessibility of the treatment area, and the type of amendment, different deployment equipment may need to be evaluated as part of the pilot study. For smaller scale applications, portable equipment may be used with more manual labor to facilitate deployment. For larger scale applications, temporary access roads may be required, which may result in limited, temporary disturbance to resource areas. Under the later scenario, the benefits and challenges of potential deployment equipment options will need to be evaluated prior to full scale application.

<u>Direct Contact of Amendment and Hydric Soil</u> - The ability to deliver amendments and ensure direct contact and mixing of the amendment with the hydric soil is a challenge given vegetative cover, leaf litter, and plant leaf cover. Vegetation may selectively be cut down to ground level outside of the growing season during seasonal die-off, leaving the root mass intact so that the vegetation can become re-established the growing season after amendment deployment without extensive restoration efforts.

Short-term Impacts to the Herbaceous Community – The amendment application process may result in the short-term create a localized elevation in pH, which may impact the herbaceous community. Vendors have advised that the short-term elevation in pH dissipates quickly and no long-term impacts are observed. Consequently, there are no prescribed measures to mitigate this situation. Other short-term impacts may be associated with limited cutting of vegetation (as described above), and impacts associated with installing and removing temporary access roads in resource areas.

Differences in Sorption Behavior due to Wetting/Drying Cycles – Amendments can be delivered in dry form using dry broadcasting techniques. This method relies on ground moisture, precipitation and/or surface water/ groundwater inundation to wet the amendment and "seat" it onto the hydric soils. Because the objective is to apply reagent while minimizing active physical alteration of the surface, soil aerators and other conventional seed seating equipment may not be appropriate. Amendment application deployment via various equipment types can be evaluated by measuring thickness and horizontal coverage during pilot studies.

### 5.4.1 General Considerations for Selecting a Delivery Method

Relatively low-tech amendment delivery methods are well established for upland soils and subaqueous sediments and are routinely used in related fields such as construction of subaqueous sediment caps, soil stabilization, landscaping, and a variety of agricultural practices. Potential non-invasive delivery techniques include methods such as dry broadcasting and slurry application using conventional landscaping or construction equipment. Solid/dry form amendments can be applied manually with the use of dry casting or pneumatic delivery equipment, as used in landscaping applications for mulch. This method of deployment allows for the distribution of the amendment over the treated remedial footprint and relies on other mechanisms to bring the amendment in contact with the contaminant(s) of concern. Slurry form amendments can be applied via pressurized hydraulic delivery systems such as a hydro-seeder. This section identifies some general considerations associated with selecting a delivery method and provides examples of equipment that may be used to implement each method.

The innovative aspect of the technology is primarily associated with delivery of sequestration agents to wetland soils in such a way as to ensure effective distribution and permanent incorporation into the soil matrix, while minimizing disturbances to wetland ecology. The majority of amendments under consideration can be applied in solid or liquid (slurry) form, each requiring consideration with regard to the specific application. Factors to consider include, but are not limited to the hydrologic conditions of the candidate site (such as subaqueous or tidal conditions) and vegetative cover. Amendment vendors for commercially available solid form delivery mechanisms such as Sedimite™ and AquaBlok® can facilitate deployment methodology and equipment selection and can address distribution and stability concerns for subaqueous and/or tidally influenced applications. It is possible to work with the manufacturers of these products to customize material formulations to optimize treatment. The technology assumes that naturally occurring mechanisms (e.g., bioturbation and herbaceous root growth) as well as water fluctuations due to periodic wetting-drying cycles will aid vertical mixing of the amendment into the hydric soil once it has been deployed.

The selection of the most appropriate application technology for a site will depend upon the sequestration agent, the nature of the wetland environment (tidally influenced, periodically inundated, etc.), the availability of support facilities (electrical power, water, etc.) access to the wetland and availability of the application equipment.

#### Pelletized Material Placement Method

Pelletized material can be delivered to wetland systems using a dry broadcast method (see Figure 5-1) such as a bark blower, telebelt (a telescoping conveyor boom mounted on a tire or track vehicle), a stone slinger, an excavator, or by manual technologies (e.g., wheelbarrow). Each placement method is summarized below with regard to reach, access considerations, and quality assurance.

Figure 5-1 Dry Broadcast of Activated Carbon (ESTCP Project Number ER-200825)

***Bark Blower***. A bark blower is typically used to pneumatically deploy bark mulch. Based on a recently completed Field Demonstration for ESTCP Project Number ER-200825 in the Canal Creek wetland system, located within the Aberdeen Proving Ground (APG) (Aberdeen, MD), (NAVFAC EXWC, *in preparation*), deployment rates vary based on the distance of deployment. Specifically, deployment rates ranged from slightly more than 1 ton per hour (tph) with 200 linear feet (lft) of hose to slightly more than 2 tph with 100 feet of hose. Each of eight treatment plots received approximately 3.3 tons (approximately 6,550 pounds) of AquaBlok®; deployed with a bark blower. The AquaBlok® pellets were 5% activated carbon by mass, so the effective activated carbon rate ranged from 124 pounds activated carbon per hour (lbcph) with 200 lft of hose to 215 lbcph with 100 lft of hose. Clogging issues were noted in the hose during deployment (especially with longer sections of hose), which affected production rates. Uneven terrain caused low spots in the hose, which increased the opportunity for clogging using this deployment technology. As such, this technology should be considered for smaller applications and/or for applications where the treatment area is in close proximity to the deployment equipment.

***Telebelt***. The telebelt is a telescoping conveyor boom attached to a dump truck or other vehicle that is used to convey earthen material from the truck using a low speed conveyor belt. This equipment is often used to reduce handling on large construction sites. The telescoping conveyors range in length and extend up to 150 feet. When deploying product, the conveyor will often discharge the material an additional distance (10-20 feet) beyond the extended boom depending on the rate of deployment (speed of the conveyor belt). The feed conveyor can be rotated approximately 330$^o$. Telescoping conveyor booms offer a high level of control over product application and can deploy materials at a rate of about 500 tph; however, the actual rate of placement will likely be much lower as the boom and vehicle location will need to shift sequentially to produce full coverage over the deployment area. Also, the use of this piece of equipment will require unobstructed access to the treatment areas. Forested wetlands may preclude the use of this technology as the trees will limit movement of the telescoping conveyor boom. Also, if deployment distances exceed the approximate 150 foot distance from the vehicle, temporary access roads into the wetland may be required to allow complete coverage of the target areas.

***Stone Slinger***. A stone slinger is a conveyance structure attached to a dump truck chassis that is used to propel earthen materials from the truck via high speed conveyor onto a prepared landscape. This equipment is generally used in construction and landscaping. The distance material is propelled is dependent on the length of the boom, the speed of the conveyor and the size of the material. Readily commercially available equipment can sling pellet-sized material projected for this demonstration distances up to 90 feet and over a rotational angle of 220$^o$ from one location. Placement quality control is a function of the material uniformity and environmental conditions at the time of placement. The rate of deployment can be on the order of approximately 40 tons per hour utilizing this piece of equipment. Because the conveyance is high speed, quality control (consistency of distribution) may be more challenging than other methods of deployment. Also, similar to the telebelt, temporary access roads into the wetland may be required to accomplish complete coverage for larger applications.

***Low Impact Swamp Type Equipment (e.g. excavator type)***. Standard earth moving equipment may also be used to dry broadcast amendment. This equipment could distribute the amendment one bucket at a time. Long reach, low ground pressure excavators, pontoon excavators, and or barge mounted excavators could also be used. Although deployment rates will be much slower than other methods

using this technology (around 30 tph), quality control will be easier to manage. This method of deployment is best suited for small treatment areas so that temporary access roads are not required.

***Manual Placement*.** In areas not accessible by equipment described above, manual placement by hand casting can be conducted. Hand casting allows the amendment to be applied to treatment areas that are too small for mechanized systems to cover and stay within the boundaries of the treatment area. It may also be a viable delivery method for areas where heavy equipment may cause damage to the wetlands vegetation or soil structure. Manual placement requires significant labor effort compared to the other methods, but equipment costs are much lower. Quality control will be optimal with this delivery method as progress can be checked continuously because of the rate of placement (less than 1 tph). The rate of placement will be dependent upon the labor employed to perform delivery.

***Deployment from Aircraft or Boat*.** In subaqueous applications, the most common form of placement is mechanical placement from a barge or boat. For sites with very challenging access issues (e.g., extremely remote sites), delivery via rotary wing aircraft (e.g., helicopter) may prove effective. For these instances, the size of the project would dictate the cost effectiveness of using either of these deployment methods. The rate of deployment and QC requirements will vary depending on the application method and remoteness of the site.

### Slurry Placement

Slurried agents can be applied to the hydric soil via pressurized hydraulic delivery systems (Figure 5-2). A couple examples of these types of delivery systems are identified below along with a discussion of reach, access considerations, and quality assurance.

**Figure 5-2 Carbon Slurry Placement (ESTCP Project Number ER-200825).**

***Hydro-seeders.*** Hydro-seeders are designed to rapidly apply slurries to large areas. They have an attached tank with mechanical agitators and/or re-circulating pumps that function to mix and keep the solids in suspension. Hydro-seeders range in size from small trailer mounted units to large truck mounted units. Hydro-seeders can deliver product at significant distances from the pump, with typical hose lengths of 300 – 500 feet. As such, this delivery method allows the most flexibility with regard wetland access logistics. They are generally limited to a solids percentage of less than 10%. The application rate of the slurry will be limited by the amount of water that can be applied to the wetland soils before the slurry is no longer absorbed and begins to flow off the target area. For this reason, there can be quality control challenges when employing this method. Depending on the saturation and hydraulic conductivity of the soils, multiple applications may be necessary to achieve the desired mass application rate. Under perfect conditions, the application rate can be as much as 1,200 lbcph (significantly higher than the other delivery methods described herein).

***High Solids Sprayers/Spreaders.*** High solids sprayers or spreaders can handle slurries with solids of 30% or more by weight. Examples include sludge sprayers, grout pumps, or manure spreaders. With a high solids spreader, the AC slurry can be applied similar to a semi-liquid solid. This allows the AC to be applied without the concern that the slurry will flow off the target area. Flow rates are generally lower than the hydro-seeder; however, due to the higher percentage of solids in the slurry, the mass flow rate is approximately the same. Quality control is more difficult with the high solids sprayers because the slurry has a thicker consistency, making it more difficult to spread it evenly.

As discussed above, there are several options available for material placement – each having its advantages and disadvantages. Table 5-1 summarizes potential advantages and disadvantages of each, Table 5-2 (USEPA, 2013) outlines examples of sites using various placement methods of the proposed amendment, and Table 5-3 illustrates sites where various delivery methods of AquaBlok® have been demonstrated (AquaBlok®, Ltd, 2013; USEPA, 2013). Selection of the most appropriate deployment method will be dependent upon several factors, including, but not limited to, site access, size and type of wetland targeted for deployment, hydrologic conditions (dry/subaqueous), quantity of material requiring deployment, quality control requirements, and other site-specific factors. In general, the methods of deployment that result in higher production rates typically become more challenging with regard to quality control (the quicker the material is being deployed, the more challenging it is to regulate distribution). Also, some of the deployment methods that require the use of telescoping booms can be challenging in wetlands with mature tree growth. Lastly, site access will be a factor in selecting the appropriate deployment equipment to minimize the disturbance associated with temporary access. In some cases, a combination of deployment methods may provide the best solution. For example, for larger sites that have good perimeter access, a Telebelt may provide 80-90% coverage, but due to the presence of some trees, 100% coverage will not be possible. In this case, material could be deployed in the remaining areas either by hand, or by using a bark blower. In these cases, engineering judgment may be required to develop the most appropriate and cost-effective deployment plan.

**Table 5-1 Delivery Methods Advantages and Disadvantages**

| Delivery Method | Advantages | Disadvantages |
|---|---|---|
| Pelletized Delivery Methods | -Can be formulated for most amendments or multiple amendments for placement as an aggregate<br>-Under the correct placement conditions can be placed uniformly with good precision on thickness (good quality control)<br>-Can be applied with a tackifier to aid in material retainage in submerged or periodically inundated wetlands<br>-Capable of being deployed by several available methods. | -May require removal of dense vegetation to allow even contact of amendment with the soil<br>-Uneven ground surface may result in uneven distribution of amendment (amendment will collect in low spots) resulting in the need for more rigorous inspection and potentially hand or mechanical raking<br>-Generally larger particles of amendment are applied compared with slurry application potentially slowing down bioturbation and mixing with underlying soils<br>-Equipment placement may generate particulates |
| Slurry Delivery Method | -Can be tremied from a remote staging area for even flow control<br>-Flowability of amendment should result in higher distribution rates vs. pelletized delivery methods<br>-Placement is minimally invasive and likely won't require removal of dense vegetation to allow contact of amendment<br>-As a slurried reagent, no air impacts are likely | -Slurried material is less resistant to displacement during periods of inundation<br>-Requires water source for mixing amendment along with a power mixer to keep amendment entrained<br>-Loss of amendment during period of inundation or stormwater runoff may increase turbidity to local water body<br>-More challenging quality control as the amendment layer will typically be much thinner vs. pelletized method.<br>-Cold weather delivery challenges |

**Table 5-2 Delivery Methods of Varying Amendment Type for Superfund Sediment Sites**

| Placement Method | Amendment Type | Site Name |
|---|---|---|
| Deployed by crane or barge (off-shore) or backhoe (near-shore) | Stone with Organoclay$^{TM}$; stone and sand; stone, sand/ Organoclay$^{TM}$ with Organoclay$^{TM}$-filled reactive core mat* attached to Tensar Marine Mattress | Central Hudson Gas & Electric Corp, North Water Street MGP Site, Poughkeepsie, NY |
| | Reactive Core Mat* attached to Tensar Marine Mattress | Former MGP, Everett, MA |
| | Reactive Core Mat with Organoclay$^{TM}$ | Salem MGP, Salem, MA |
| | Reactive Core Mat | Former industrial site, Silver Lake, MA |
| | Apatite; Coke Breeze mat | Anacostia River Demonstration Project, Washington DC |
| | Reactive Core Mat with Organoclay$^{TM}$ | Former creosoting wood treating site, Escanaba, MI |
| | Reactive Core Mat with Organoclay$^{TM}$ | Gasco, Portland, OR |
| | Reactive Core Mat with Organoclay$^{TM}$ | McCormick & Baxter Creosoting Co. (Portland Plant) Superfund Site, Portland, ORCanal Creek, Aberdeen Proving Ground, MD |
| | Activated Carbon in the form of SediMite | |
| Rototiller (with/without rotors) and Tine sled | Activated Carbon | Grasse River, Massena, NY |
| Telebelt | Granular carbon with a coarse sand cap | Berry's Creek, Bergen County, NJ |
| Vortex TR Aquatic Spreader | Activated Carbon in the form of SediMite | Berry's Creek, Bergen County, NJ |
| | Activated Carbon in the form of SediMite | Bailey Creek, Fort Eustis, VA |
| | Activated Carbon in the form of SediMite | Canal Creek, Aberdeen Proving Ground, MD |
| Manual Placement (via unrolling, commercial divers, settling, etc.) | Mat | Cocheco River, Dover, NH |
| | AquaBlok | Chattanooga Creek, Tennessee Products Superfund Site, OU 1, Chattanooga, TN |
| | Reactive Core Mat (60% AC) | St. Louis River/Interlake/Duluth Tar Superfund Site (Stryker Bay), Duluth, MN |
| | Mat | Cottonwood Bay, Grand Prairie, TX |
| | Coal, sand, gravel | Spokane River Upriver Dam PCB Site (Deposit 1), Spokane, WA |

Source: (USEPA, 2013).

**Table 5-3 Demonstrated Delivery Methods of Amendment Types**

| Delivery Method | Amendment Type | Site Location | Setting/Purpose |
|---|---|---|---|
| Aircraft | AquaBlok® | Eagle River Flats Superfund Site, Fort Richardson, AK | Wetland (freshwater, with periodic brackish tidal inundation). Encapsulation of contaminated sediments. |
| | | Ottawa River, Toledo, OH | River (freshwater) with estuary characteristics. Encapsulation of contaminated sediments. |
| Excavator | AquaBlok® | Upper Outfall, Macon, GA | River (freshwater). Encapsulation of contaminated sediments. |
| | | Deer Creek Superfund Project, St. Louis, MO | River (freshwater). Encapsulation of contaminated sediments, within the context of a bank stabilization project. |
| Stone-slinger | AquaBlok® | Kearny Marsh, Kearny, NJ | Freshwater marsh. Encapsulation of contaminated sediments. |
| | | Chattanooga Creek, Chattanooga, TN[1] | Freshwater creek and floodplain area. Seal/Liner construction to isolate mobile contaminants in surrounding area. |
| Slurry via Hydroseeder | Activated Carbon | Berry's Creek, Bergen County, NJ | Tidal marsh covered with phragmites. Encapsulation of contaminated sediments. |
| Slurry injector and Rotovator | Activated Carbon mix | Hunters Point Shipyard Superfund Site, Parcel F, San Francisco, CA | Tidal mudflat. Encapsulation of contaminated sediments and stabilization of PCBs and reduction of bioavailability. |

Note: [1]Deployed via land-based stone dump truck and long-stick excavator. (AquaBlok®, Ltd, 2013; USEPA, 2013).

### 5.4.2 Site Access Considerations

As previously discussed, site access will be a key factor when considering amendment application. Often times, site access will dictate which deployment method(s) is most appropriate for a site. When upscaling a project from a pilot demonstration, site access, equipment and material staging areas, and wetland access road placement, if required may be considered. In some cases, it may be advantageous to employ two or more deployment methods to minimize disturbance to sensitive resource areas. The pros and cons for employing multiple delivery methods will have to be evaluated with regard to the additional cost for mobilization and demobilization versus project duration.

### 5.4.3 Scheduling Considerations

The time of year for which the deployment activities are scheduled should incorporate environmental work windows, comply with environmental permit restrictions, and minimize growth season disturbances. Examples may include work window limitations to account for migratory and/or breeding fish or birds or periods of heavy recreational use. As another example, at densely vegetated sites that may experience seasonal dormant periods for vegetation growth, it may be advantageous to deploy amendments during non-growing seasons (late fall/early spring) before foliage becomes well established. This will optimize amendment contact with impacted hydric soils and minimize potentially deleterious impacts (e.g., carbon dust on foliage inhibiting photosynthesis). Deployment under sub-

freezing conditions, although potentially advantageous for minimizing disturbance to vegetation during the growing season, can present challenges. Specifically, slurry applications can become problematic due to the need for providing and maintaining a water source at the site. However, frozen ground can facilitate personnel access to otherwise soft-subgrade areas to facilitate amendment deployment.

# 6.0 Post-Implementation Evaluation and Long-Term Monitoring

Following *in situ* active remediation of wetland hydric soils, the efficacy of the treatment and the success of the remedy in meeting remedial action objectives should be assessed to continue the development and advancement of the technology and associated monitoring and construction methods. Measured/observed performance metrics are compared to the success criteria to determine whether the performance of the remedy was acceptable or not and if not, identify potential corrective actions for the site or identify innovation needs to improve the state of the practice for this technology.

Treatment effectiveness of the *in situ* wetland remediation technology should be evaluated for each site using a monitoring program that includes both baseline characterization activities (i.e., time zero monitoring) and post-treatment monitoring. Post-treatment monitoring activities will likely be conducted for several years following amendment application. The frequency of which will be project specific. An example post-treatment monitoring schedule may include year 1, 2, 5, and 10 monitoring events. The frequency and extent of monitoring can be revisited following each event as data trends become established. It is ideal to implement identical monitoring protocols in the baseline monitoring effort and in subsequent efforts.

Monitoring tasks may include chemical, physical, toxicological, and ecological evaluations to assess the efficacy of the sequestration agent application, and to ensure that the wetland community at a site has not been altered (or recovers from any short-term impacts) due to implementation of the *in situ* treatment. Table 6-1 provides examples of some anticipated monitoring outcomes if treatment is effective and detrimental impacts from construction-related activities are temporary. The performance objectives and the anticipated outcomes may be stated with greater specificity as higher resolution monitoring methods are employed and with greater monitoring frequency. It is best if post-treatment monitoring for most ecological elements is performed during peak growing season foliage conditions (i.e., present approximately between March and October of the year), however it is recognized that some measures of bioavailability (e.g., metals in pore water) may be most conservatively measured in winter months. Ecological health monitoring may include the qualitative assessment of the plant and resident animal community. In addition, hydric soil conditions, changes in hydrology, contaminant stabilization (through decrease in contaminant bioavailability), and risk reduction should be examined. For comparative and data usability purposes, it is recommended that all samples be spatially and temporally consistent (e.g., same fixed location during the spring [growing season] months). Examples of performance criteria and performance confirmation methods for metrics observed/measured in each of these categories are presented on Tables 3-2 through 3-4.

Monitoring after an extreme weather event such as a hurricane, flooding, or ice scour is also necessary. Extreme weather can cause erosion and lead to dispersion of contaminated sediment. Tasks to monitor the efficacy of remediation within the bounds of extreme levels of hydrodynamic forces are necessary. Considering the possibility and intensity of an extreme weather event is key to understanding the possible impacts of the force on the recommended remedy. According to the USEPA, 2005 sediment remediation guidance with respect to MNR and capping, project managers are encouraged to consider a wide range of effectiveness scenarios for site conditions and remedy performance. Decades-long performance of amended caps or in situ remedies has not been evaluated, although pilot-and full-scale amendment remedies indicate strong performance over 1-5 years. The lifetime of the amendments could be limited by sorption capacity or by deterioration (USEPA, 2013). Therefore, it is recommended that monitoring of the treatment efficacy be continued after the demonstrated period of strong performance. Table 6-1 identifies potential conditions that may warrant adaptive management or maintenance actions, which may be indicated if treatment efficacy is not indicated, becomes reduced, or in response to extreme events. The examples are not meant to be comprehensive but are provided for illustrative purposes.

For bioaccumulative COCs, a primary trigger when evaluating in situ wetland remediation monitoring results is an increase in tissue residue concentrations of resident invertebrates, fish, or wildlife. An increase in pore water concentrations may also indicate a need for additional more focused evaluation and/or response actions (e.g., Table 6-1).

Passive sampling provides a good estimate of what is potentially bioavailable and passive samplers can be deployed for up to several months at a time, resulting in a time-averaged representation of COC concentrations (EPA, 2012). Passive sampler deployment directly into the environment for a period of time allows for periodic monitoring of potential changes in COC concentrations during the duration of long-term monitoring. Overall, passive samplers give a more accurate estimate of hydrophobic contaminant concentrations in the dissolved phase (EPA, 2012). Ongoing developments in sampling technologies hold promise for enhanced adaptive management decisions at *in situ* remediation sites as treatment technologies are more widely applied. For example, the new Sediment Ecotoxicity Assessment Ring (SEA Ring) technology developed under ESTCP project ER-201130 provides in situ assessment of advective exposure pathways at contaminated sediment and surface water sites via in situ bioassay chambers and passive sampling devices.

**Table 6-1 Example Monitoring Metrics, Anticipated Outcomes and Potential Adaptive Management Triggers**

| Monitoring Metrics | Anticipated Outcomes if Treatment is Effective | Potential Adaptive Management Triggers |
|---|---|---|
| Chemical | ▪ Pore water concentration decreases with time<br>▪ Pore water concentration decreases relative to reference area<br>▪ A statistically significant percent change in pore water partitioning to soil is achieved | ▪ Pore water concentration rebounds above project criteria threshold<br>▪ Pore water concentrations in reference areas decrease more rapidly than in treated areas<br>▪ Partitioning to soil is not observed or is not significant |
| Physical | ▪ No change to site hydrology<br>▪ No change to soil bulk density | ▪ Indicator parameters (e.g. turbidity) degraded<br>▪ Bulk density increases due to compaction or decreases due to disturbance |
| Toxicological | ▪ Decrease in macro-invertebrate, fish, or other receptor tissue concentrations | ▪ Bioavailability and tissue concentration increase (as measured by $K_{bulk/PW}$ or $K_{bulk/LV}$) |
| Ecological | ▪ Increase in plant abundance, diversity, and cover<br>▪ Increase in early life stages and/or adult amphibians<br>▪ Increase in invertebrate community/population health metrics<br>▪ No increase in invasive exotics | ▪ Decrease in plant abundance, diversity, and cover<br>▪ Decrease in early life stages and/or adult amphibians<br>▪ Decrease in community health or population<br>▪ Shift in community structure toward invasive species |

# 7.0 Cost Analysis

A cost analysis was performed to provide order-of-magnitude costs for full scale application of the technologies described in this FGM. The cost estimates presented herein can be used to compare *in situ* wetland remediation technologies to more conventional remedial technologies such as source removal and restoration. Ghosh et al. (2011) and Patmont et al. (2013) have presented cost estimates for the application of *in situ* remediation by AC, which compare favorably to cost estimates of dredging and disposal. For example, costs of dredging the Hudson River have been reported to be $15M per hectare (ha) for phase I of the clean-up (Hill, 2010 as cited by Ghosh et al., 2011) but costs for active *in situ* treatment by AC are an order of magnitude or more lower, ranging from $150,000/ha to $0.5M/ha (Patmont et al., 2013)

Wetland site variables such as the size and type of wetland requiring remediation, access, vegetation conditions, topography, water level conditions, and other site conditions may necessitate a broad variety of approaches in the method and types of deployment equipment for *in situ* remediation. Several factors require consideration for the full scale application of this technology, one of the most limiting of which is potential site access. Site access may significantly affect cost as follows:

**Scenario 1**: Equipment can deploy amendments to wetland from adjacent upland areas such that access roads or swamp mats will not be required within the wetland.

**Scenario 2**: Equipment will require access roads or swamp mats within wetland areas in order to deploy amendments.

Therefore, a significant portion of the construction cost can be associated with equipment mobilization and site preparation. The cost per acre for mobilization and site preparation decreases as the treatment area increases. As such, example costs are presented for three different size wetland areas (1, 5 and 10 acres).

Lastly, existing equipment available in the marketplace can readily be adapted to deploy treatment products to wetland hydric soils. Examples of four different deployment options include those discussed previously in Section 5: a bark blower, stone slinger, telebelt and hydro-seeder. Several other options exist for deployment equipment for sites with challenging access issues, including the use of barges and/or helicopters or other equipment; however, these installation methods were considered to be atypical situations for wetlands access, and as such, cost estimates presented in this FGM do not include those process options.

## 7.1 Cost Model

Table 7-1 presents an example cost model for the full-scale implementation of the technologies described in this FGM, assuming the typical scenarios described above. Major cost elements related to the technologies include: treatability study, mobilization, treatment technology, implementation, demobilization, long term monitoring, and reporting. The assumptions associated with these elements are described in the following sections. It should be noted that design and permitting costs were not included in the example provided as these costs are assumed to be approximately consistent between remedies (traditional removal vs. in-situ sequestration).

The cost model represented in Table 7-1 predicts costs in the range of $72,000 - $210,000/acre on a 10-acre site for PAC and pelletized carbon with a weighting agent, respectively. Patmont et al. (2013) predicted a range between $60,000 - $200,000/acre for a 10-acre site. The relatively minor differences between the costs represented in Table 7-1 and Patmont et al. (2013) can be attributed to the incorporation of costs for mobilization, demobilization, and binding/weighting agents in the example model.

Comparatively, a similar project conducted by Dr. Charles Menzie (ER-200835) using SediMite projected costs of $90,000 to $200,000 per acre. Additionally, SediMite™ may eliminate the need for substantial habitat restoration because of the enhancement, rather than the disturbance, of the sediment ecosystem (Menzie, 2011).

**Table 7-1 Cost Model for In Situ Contaminant Sequestration in Wetland Hydric Soils**

| Cost Element | Element Components | Cost per Treatment Area (acres) | | |
|---|---|---|---|---|
| | | 1 Acre | 5 Acre | 10 Acre |
| Treatability Study | Labor<br>Materials<br>Analytical laboratory costs | \$20 - \$25 | \$25 - \$50 | \$25 - \$50 |
| Mobilization | Access Road, Dry/Wet Deployment Roads<br>Shipment of equipment and supplies | \$15 - \$70 | \$50 - \$350 | \$100 - \$600 |
| Material Cost[2] (Amendment) | Material cost (including manufacturing) | \$20 - \$40 (PAC)<br>\$50-\$70 (Pellet with weighting agent) | \$100 - \$200 (PAC)<br>\$250-\$350 (Pellet with weighting agent) | \$200 - \$400 (PAC)<br>\$500-\$700 (Pellet with weighting agent) |
| Implementation | Equipment Rentals | \$5 - \$15 | \$10 - \$40 | \$15 - \$75 |
| Demobilization | Labor (amendment deployment and application thickness confirmation measurements)<br>Access Road, Dry/Wet Deployment Roads Restoration | \$15 - \$30 | \$40 - \$130 | \$70 - \$275 |
| Long-term Monitoring | Shipment of equipment and supplies<br>Travel and labor (sampling and field surveys) | \$25 - \$50 | \$100 - \$150 | \$200 - \$250 |
| Reporting | Shipment of equipment and supplies<br>Laboratory costs<br>Annual and 5 year reporting | \$75 - \$100 | \$75 - \$100 | \$75 - \$100 |
| Project Management | Labor | \$35 - \$50 | \$35 - \$50 | \$35 - \$50 |

Notes: [1]All costs are in \$1,000s and based on a cost model presented in Final Report: *In Situ* Wetland Restoration Demonstration ESTCP Project Number ER-200825 and material costs presented in Patmont et al. (2013). [2]Cost of shipping not included because it will vary with quantity and distance from manufacturer/supplier.

### 7.1.1 Treatability Study and Remedial Design

A Treatability Study will often be required to determine the type(s) of amendments to be used for full scale application as well as the optimal application rate(s) needed to effectively sequester contaminants. Costs for this study will typically vary by contaminant, monitoring metrics, surface area of a site, number of different soil types at site, and other site-specific variables. Costs for certain organic compounds (e.g., high resolution PCB congener analysis) are expected to be of a higher magnitude than typical costs to assess the bioavailability of inorganics (e.g. metals and AVS/SEM analyses). The Treatability Study will typically be comprised of laboratory testing using site specific materials and available amendments. The results from the Treatability Study will be used as a basis for full scale design and implementation.

Components of a typical Treatability Study include:

1. Preparation of a site specific work plan to be approved by relevant stakeholders to reach consensus on performance criteria,
2. Phased laboratory work which may include an evaluation of amendment effectiveness, amendment dose optimization, and bioassays such as toxicity testing or bioaccumulation studies, and
3. Preparation of a report detailing the findings of the study, as well as recommended paths forward for implementation.

The potential costs for the treatability study may also range depending on the density or frequency of sampling but typical costs for a wetlands site is expected to be $20,000 to $50,000.

### 7.1.2 Permitting

Because the technologies described in this FGM include the introduction of fill to a resource area (albeit a minimal quantity of fill), federal permitting (e.g., USACE, Section 404 of the Clean Water Act) and possibly State/local permitting may be required. Because this permitting may also be required for more conventional remedial approaches (such as source removal), and because these costs are fairly well documented and do not vary significantly based on the technology employed, permitting costs were not included in this cost model, but should be planned for when evaluating this technology. Cost elements may include application and review fees, generation of maps and site information, and stakeholder meetings.

### 7.1.3 Mobilization and Site Preparation

Typical mobilization costs include the cost for mobilizing construction equipment and temporary facilities and supplies to the site in support of the proposed work activities. In addition, temporary staging areas and access roads may be necessary in the cost estimate in order to mobilize and stage equipment and materials proximal to the proposed treatment areas to facilitate deployment. Unless suitable site features already exist (access roads, cleared lots, etc.), these laydown areas may need to be installed as part of site preparation activities. In order to install these features, limited clearing and grubbing activities may be required. Depending on the condition of the subgrade and potential permit requirements, geosynthetics (geotextiles and/or geogrids) and a 12-18” deep layer of structural fill (e.g., processed gravel) may be required to provide adequate bearing capacity to support the anticipated construction equipment. Where possible, access roads and staging areas should be constructed in upland areas; however, depending on the wetland configuration and extent of proposed amendment application, temporary access roads may need to be constructed in wetland areas (within the proposed treatment area). Swamp mats may be used if equipment access to the wetland areas is required. Access roads typically need to be a minimum of 15 feet wide, but may need to be wider for specialized equipment such as a Tele-belt (30 feet wide minimum).

For the purpose of the cost analysis presented in this FGM, mobilization costs may include the following components:

- **Site Access Road and Staging Area** – If necessary, minimal clearing/grubbing and grading may be required to allow for installation of a site access road and staging area. If no access roads need to be constructed, then the cost of materials for the assumed road dimensions would not be realized.
- **Amendment Deployment Road Construction** – If necessary (e.g. Scenario 1), limited clearing/grubbing and grading may be required to allow for installation of the deployment road.
- **Wetland Access Road Construction** – If necessary (e.g. Scenario 2), swamp mats may be used to establish access in such a way as to optimize efficiency, and ideally clearing/grubbing and grading would be avoided, or if required, minimized.

The cost estimate for mobilization using typical conditions ranges from $37,000/ha to $175,000/ha ($15,000/acre to $70,000/acre) and decreases per unit area as the size of the area being treated increases

### 7.1.4 Material Cost

A variety of treatment products and dosing rates are possible but an application treatment of pelletized AC to an average dose of 3% by mass in the top 10 to 15 cm of the BAZ is anticipated to be typical for most wetland hydric soil. A variety of commercially available pelletized AC and PAC slurry products should be considered to provide a range of potential costs for a design goal of 3% AC in the top 15 cm of the BAZ. Cost estimates for a soil cover system consisting of a natural organic carbon containing topsoil and sand mixture may also need to be included for a baseline comparison.

Other amendment products are available and can be customized to site-specific needs but are expected to fall within the range of treatment costs provided here. Using a bulk AC cost of about $2.20 US Dollars (USD) per kilogram, Ghosh et al.(2013) provide a cost estimate of about $75,000 per hectare (ha) ($30,400 per acre). This is consistent with material cost estimates presented by Patmont et al (2013), who estimated material costs at $49,400/ha ($20,000/acre) to $98,800/ha ($40,000/acre).

### 7.1.5 Implementation

The size, location and access to the treatment area will often dictate the type of equipment and labor effort required for deployment of the preferred amendment, which thereby influences cost and schedule considerations. Typical equipment described in Section 5 can be used to deploy particulate amendment, and/or a soil cover system. For the application of PAC slurry, a hydroseeder is a viable and cost effective option. The following equipment limitations and production rates may be used as a basis for costing:

- **Bark Blower** – Assume a maximum extent of deployment from the unit is 50 feet and that the unit can deploy material at a rate of two tons per hour, which will vary in the field if the equipment needs to be moved frequently. To account for repositioning of the equipment, it may be assumed up to 12 tons can be deployed per day utilizing this piece of equipment.
- **Stoneslinger** – Assume a recommend extent of deployment (i.e. reach) up to 80 feet from the truck at rate of 40 tons per hour; therefore, when factoring in loading and repositioning up to 240 tons can be deployed per day.
- **Tele-belt** – Assume an extent of deployment up to approximately 150 feet from the truck. The operator needs to keep tight control of the boom position and conveyor belt rate since this piece of equipment has the capacity to deploy material at a rate of 250 tons per hour. In order to allow for even placement of the material, the deployment rate should be managed at a rate of approximately 150 tons per hour; therefore, when factoring in loading and repositioning, assume that up to 900 tons per day can be deployed using this piece of equipment.
- **Hydroseeder** - Assume that a mixture of water and PAC (at a mixing ratio of 35-40% carbon by weight), can be applied at a rate of approximately 5 acres per day up to 500 feet from the unit. Hydroseeders with capacities of 600, 1,000, and 4,000 gallons are readily available in most regions of the country.

Even with the potential array of deployment methods that are possible, production rates, and site logistical challenges, the cost of implementation is not likely to be a cost driver compared to other factors (e.g. material costs, mobilization/demobilization). Typical implementation costs presented in Table 7-1 suggest that the cost of this element may be ½ to ¼ the cost per unit area of other project elements. In fact, the costs of implementation also may decrease significantly as the size of the treatment area increases. Cost estimates reported by Patmont et al (2013) for placing AC treatment products are similar in magnitude when mobilization/demobilization are considered and ranges from $74,000/ha ($30,000/acre) to $173,000/ha ($70,000/acre). Patmont et al (2013) note that mechanical mixing of a treatment technology into soil or sediment may cost upwards of $100,000/ha (about $40,000/acre)

### 7.1.6 Demobilization

Typical costs encountered during demobilization related activities involve shipment of equipment and excess supplies from the site, as well as the removal/restoration of the areas impacted during the deployment process, including the site access roads, deployment roads, and the equipment storage/staging areas. Demobilization costs may include the following assumptions:

- Access roads and staging areas are removed and shipped off-site as "clean fill". Therefore, the cost estimated includes the removal and shipping of the process gravel only (i.e. no disposal costs).
- The removal/disposal of the geosynthetics (geotextiles and/or geogrids) can be disposed as general debris in an appropriately sized roll-off dumpster with cover and associated delivery/pickup and disposal fees.
- Removal and decontamination of the swamp mats, the decontamination pad, the waste profile laboratory, and disposal costs at a properly licensed facility are costs typically encountered.
- Restoration costs (seeding and plantings) for a limited area of wetlands that may be disturbed to provide access for amendment deployment should be anticipated, as appropriate.

### 7.1.7 Long-Term Monitoring and Reporting

Because this technology involves the *in situ* sequestration of COCs, long-term monitoring activities are likely to be necessary to demonstrate remedial success. Also, because this technology has a limited case study history, specific long-term monitoring requirements have the potential to vary significantly from site to site and may depend on regulatory oversight conditions. Lastly, because of the anticipated potential duration of long-term monitoring and reporting (10 to 20 years), this is a significant component of the overall cost of this technology.

Long-term monitoring activities can typically be assumed to include periodic sampling and evaluation tasks performed during the growing season following amendment deployment and will often involve sampling of hydric soil, pore water, and possibly tissue samples in the treated area. Monitoring events may potentially consist of activities such as collecting:

1. Porewater concentrations from hydric soil grab samples;
2. Bulk hydric soil concentrations from grab samples;
3. Benthic receptor tissue concentrations from organisms exposed to hydric soils under laboratory conditions (e.g., bioaccumulation assays);
4. Field collection of organisms for tissue residue analysis;
5. Laboratory toxicity testing, and/or
6. Ecological sampling.

For the purposes of preparing a cost estimate to help guide end-users of this FGM, the following typical elements may be considered for a monitoring program:

- Monitoring includes sampling at routine intervals over a 10 to 20 year period. This duration is provided as an example of potential long term monitoring durations.

- A pre-treatment baseline “Time Zero” sampling event is included.
- Analyses may be tailored to reflect the data quality objectives so that routine sampling events may vary by frequency. For example, the 10 and 20 year post application events (if applicable) may include the full suite of analysis (bulk soil, pore water, and tissue) in order to gauge the long term effectiveness in reducing the bioavailability of the contaminants. Annual sampling may consist only of ecological field surveys as the treatment products described in this FGM do not decrease total concentration of contaminants in bulk soil (Ghosh et al., 2013), but monitoring programs will vary, depending on what the regulatory agencies deem appropriate.

As the size of the candidate site is scaled up (e.g., 5 acres, 10 acres, etc.), the costs for long term monitoring may increase, depending upon the degree of characterization for statistical evaluation is desired. Cost estimates for long term monitoring reportedly range from $25,000/ha ($10,000/acre) to ~$125,000/ha ($50,000/acre, depending on whether sampling for treatability studies and baseline characterization activities are included (Patmont et al., 2013).

Reporting costs are assumed to include a typical brief summary report for each monitoring effort and a comprehensive report is required at the conclusion of the long term monitoring period. Thus, reporting costs may be assumed to be the same regardless of treatment area.

## 7.2 Cost Drivers

As depicted in Table 7-1, the primary cost drivers are mobilization/site preparation, amendment materials, demobilization/site restoration and long-term monitoring costs.

- Mobilization and demobilization costs become less significant to the overall project costs as the application area increases.
- Site preparation/site restoration costs are dictated by providing sufficient access for the construction equipment to effectively deploy amendment. The typical deployment equipment (telebelt, hydroseeder and stoneslinger) require stable access roads to maximize their effective reach for deployment. Depending on the configuration/layout of the wetland and other site specific conditions (type of vegetation, depth of water, bearing capacity of wetland soils, etc.), access road construction, decommissioning and restoration can make up over half or more of the overall cost.
- The type and quantity of amendment required can be a cost driver. For the deployment scenarios identified in the example cost model above, the amendment cost was ~5-12% (1 acre vs. 10 acres) of the total construction cost.

Monitoring costs can be substantial. For the immediately foreseeable future, it is likely that extensive monitoring will be required by regulatory stakeholders, given the evolving nature of these technologies. It is anticipated that, over time, less extensive monitoring will be required, once *in situ* technologies become more mainstream components of wetland remedial planning.

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# Appendix A: Soil Density and Activated Carbon Application Rate Calculations

## Soil Density and Activated Carbon Application Rate

The mass of soil in a unit volume is calculated using equation 1:

$$M = V * \rho_B \qquad (1)$$

Where M is mass, V is volume, and $\rho_B$ is the bulk density of the soil. For wetland applications, the density of the soil is not directly known. The volume is determined by the size of the plot, and by the desired depth of the amendment. Based on previous studies, the biota layer where the amendment will be mixed is restricted to the top six inches of the soil. The chosen unit volume is one square meter by 0.15 m, or 150,000 $cm^3$.

For the field demonstration site, density and porosity was not measured directly. The only physical measurement conducted by the lab was the percent solids of the samples taken in July 2009. The average soil density on a weight basis was 33.8%. An effective density and porosity can be estimated from this information and average specific gravities. The soils at the site are described as mineral soils, with low total organic carbons. Mineral specific gravities range from 2.3 to 2.9 (Lambe 1969). Percent solids in a saturated sample can be expressed by the Equation 2.

$$S_{\%} = \frac{M_{solids}}{M_{solids}+M_{water}} = \frac{(1-n)V\rho_S}{V(1-n)\rho_S+Vn\rho_W} = \frac{(1-n)\rho_S}{(1-n)\rho_S+n\rho_W} \qquad (2)$$

Where M is the mass of the solids and water in a sample, $V$ is the volume of the sample, $\rho_s$ and $\rho_w$ are the specific gravity of the solids and the water, and $n$ is the porosity of the sample. Equation 3 is the result of solving Equation 2 for porosity in terms of density and solids percentage.

$$n = \frac{(1-S_{\%})\rho_S}{(1-S_{\%})\rho_S+S_{\%}\rho_W} \qquad (3)$$

The density of water is assumed to be 1 gram per cubic centimeter. The average percentage of solids in the samples taken from the site is equal to 33.8 %. Using an assumed $\rho_s$, the porosity, bulk density, and amount of activated carbon needed per square meter was calculated. Bulk density is calculated using Equation 4:

$$\rho_B = (1-n)\rho_s \qquad (4)$$

Table A shows the results of this analysis, where column 1 is assumed, column 2 is calculated using equation 2, column three is calculated using equation 4, and column 4 is calculated using equation 1. From the Treatability Study, the desired amendment ratio is 3% by weight, so column 5 is 3% of column 4.

**Table A: AC Calculations**

| $\rho_s$ | $n$ | $\rho_B$ | $M_{solids}$ | **AC Needed ($kg/m^2$)** |
|---|---|---|---|---|
| 2.9 | 0.9 | 0.4 | 65.1 | 2.0 |
| 2.8 | 0.8 | 0.4 | 64.8 | 1.9 |
| 2.7 | 0.8 | 0.4 | 64.4 | 1.9 |
| 2.6 | 0.8 | 0.4 | 64.0 | 1.9 |
| 2.5 | 0.8 | 0.4 | 63.6 | 1.9 |
| 2.4 | 0.8 | 0.4 | 63.2 | 1.9 |
| 2.3 | 0.8 | 0.4 | 62.7 | 1.9 |

It is unlikely that the mineral specific gravity is as high as 2.9 $g/cm^3$. As can be seen from Table A, for the likely range of mineral densities, the amount of activated carbon needed is 1.9 $kg/m^2$.